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Final Draft

Evaluation of Loss of Offsite Power Events at Nuclear Power Plants: 1980 - 1996

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ABSTRACT

It is recognized that the availability of AC power to commercial nuclear power plants is essential for safe operations and accident recovery. A loss of offsite power (LOSP) event, therefore, is considered an important contributor to total risk at nuclear power plants. In 1988, the NRC published NUREG-1032 to report on an evaluation of the risk from actual LOSP events that had occurred at nuclear power plants within the United States up through 1985. This report documents a similar study whose primary objective was to update the LOSP model parameters, frequency and recovery time, using plant event data from 1980 – 1996. An additional objective is to re-examine the engineering insights concerning LOSP events.

Job Code E8247 – Special Methods and Databases

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EXECUTIVE SUMMARY

In 1988, NUREG-1032 estimated loss of offsite power (LOSP) frequency and duration, and the reliability of emergency diesel generators. One primary objective of the present study is to update the LOSP model parameters, frequency and duration, for the time period 1980 – 1996, inclusive. These parameters are needed to determine the risk implications of LOSP and station blackout scenarios. The other primary objective is to re-examine the engineering insights from NUREG-1032, using the more recent data.

The present project includes LOSP events occurring during 1980 through 1996, after the plant's full power license date. Here, LOSP is defined as simultaneous loss of electrical power to all unit safety buses, requiring the emergency power generators to start and supply power to the safety buses. For events that occurred during power operation, this report distinguishes between initiating events and non-initiators. At most plants, LOSP causes the reactor to trip, but some plant designs permit the plant to continue operating at power, with the safety buses supplied by the emergency power generators. This report calls the event an initiating event if the LOSP caused the reactor to trip. All events included in this study are LOSP events, but only the initiating events were used in the frequency analysis.

The time to recovery was defined as the time until offsite power could have been restored by following plant procedures. Often this coincided with the actual reported duration of the LOSP event, but sometimes it was smaller.

The LOSP events were grouped into three categories: plant centered, grid related, and caused by severe weather. They were also grouped according to the plant condition at the time of the event, either at power operation or in a shutdown. Finally, because about 15% of the events had very short recovery times, the events were classed as momentary if the recovery time was less than two minutes, and non-momentary otherwise. For operating plants, the frequency of LOSP initiating events was estimated. The non-initiators were not used in this estimate, even though those events might have been initiators had they occurred at other plants. The frequencies were estimated separately for momentary and non-momentary events. For shutdown plants, the frequency of LOSP events was estimated using all events. That is, the distinction between initiating events and non-initiators was not made for shutdown events; some of the shutdown events included in the analyses might not have caused a trip if they had occurred while the plant was at power. Again, the frequencies were estimated separately for momentary and non-momentary events. Finally, for each category of event, the times to recovery (of non-momentary events) were characterized. The plant condition, operating or shutdown, had little effect on the duration of the event, so it was ignored.

The analysis uses various models, depending on what the data show. For example, frequencies are presented in terms of units (individual power plants), but recovery times in terms of sites. Between-unit or between-site variation is modeled in some cases, and between-year variation in one case. Based on the data in each case, the most appropriate model was used rather than force-fitting all the data sets into a single model.

Tables ES.1 through ES.3 summarize the quantitative results of this study.

Table ES.1. Summary statistics on frequencies during power operation, for 116 units in 1188.6 unit critical years (1980 critical time was estimated).

	Plant-Centered	**Grid-Related**	**Severe Weather**
Number of LOSP initiating events, by unit (= momentary + non-momentary)	50 (= 4 + 46)	2 (= 1 + 1)	11 (= 4 + 7)
Number of non-initiators (LOSP events at power when reactor did not trip, or tripped just before LOSP)	15	1	0
Frequency of initiating events (events per unit critical year)	0.04	0.002	0.009
90% uncertainty interval on frequency of non-momentary events.	0.006 to 0.1	NA	0.003 to 0.01
Maximum number of initiating events at any unit	3	1	3
Average number of initiating events per unit	0.43	0.02	0.09

Table ES.2. Summary statistics on frequencies during shutdown, for 116 units in 455.7 unit shutdown years (1980 shutdown time was estimated).

	Plant-Centered	**Grid-Related**	**Severe Weather**
Number of LOSP events, by unit (= momentary + non-momentary)	80 (= 11 + 69)	3 (= 0 + 3)	11 (= 4 + 7)
Frequency of events (events per unit shutdown year)	0.18	0.007	0.02
90% uncertainty interval on frequency. (See report for unit-specific estimates or other details.)	0.01 to 0.54	NA	0.007 to 0.03
Maximum number of events at any unit	5	2	4
Average number of events per unit	0.69	0.03	0.09

Table ES.3. Summary statistics on times to recovery for LOSP non-momentary events.

	Plant-Centered	**Grid-Related**	**Severe Weather**
Number of events with reported recovery times, by site	102	4	9
Number of events with no reported recovery times, by site	9	0	1
Mean time to recovery	85.4 min.	203. min.	1258 min.
Median time to recovery	29 min.	160. min.	270.5 min.
Minimum and maximum times	2 min., 1675 min.	130 min., 360 min.	37 min., 7929 min.
90% uncertainty interval on recovery time (based on fitted models)	2.8 to 314 min.	NA	23 to 5009 min.

The major technical findings concerning frequencies are summarized here.

- NUREG-1032 found that plant-centered events accounted for the majority of the losses of offsite power. This study supports that finding, with plant-centered events clearly dominating LOSP frequency during power operation, as well as during non-power modes of operation. Events induced by severe weather are much less frequent, and grid-related events are still less frequent.

- LOSP frequency for plant-centered events is significantly higher during shutdown modes of operation than during power operation, by a factor of about four. The difference is present for both non-momentary and momentary events, and would be present even if non-initiating events at power were combined with the initiating events in the analysis. For severe-weather events, the estimated frequency is also higher during shutdown than during power operation, but it is hard to say whether the difference is statistically significant. For grid-related events too few events occurred to give any firm conclusion.

- For plant-centered non-momentary initiating events at power, no statistically significant plant-to-plant variability in LOSP frequency was found. A decreasing trend in time was not statistically significant, based on the 1980 – 1996 data. Therefore no trend was modeled. The annual counts were showed larger-than-expected scatter around the mean, caused in part by dependence between units.

- For plant-centered non-momentary events during shutdown, significant statistical variability was found among the plants, but not among years. Therefore, a population variability distribution was developed. Data at individual plants were used to update this overall distribution, yielding plant-specific estimated frequencies.

- The majority of plant-centered LOSP initiating events at power were caused by equipment faults (57%), with a smaller portion being induced by human error (26%). During shutdown modes, the opposite holds, with human errors being the major contributor (59%). The numbers are similar if only non-momentary events or only momentary events are considered.

- Plant-centered initiating events per year have become less frequent since the time period studied by NUREG-1032. A clear downward trend can be seen in the frequency from 1969 through 1996. No effect was found in the data that could be related directly to the Station Blackout Rule (10 CFR 50.63), which was published in June 1988.

- The LOSP frequency from grid-related events in the period covered by this report, 1980 – 1996, was very small. During this period, there were only six events that could be classified as grid-related, and some were dependent. This is less frequent than found in NUREG-1032 by a factor of about 10. No grid-related events occurred in the 1990s, in spite of the occurrence of several widespread losses of power to the public.

- During the time period of this study, there was only one complete LOSP event due to a grid disturbance. A fire near Turkey Point caused a grid failure that resulted in both units experiencing a LOSP event. *Dave, what's a complete LOSP event? Aren't all 6 complete?*

- The frequency of LOSP non-momentary shutdown events due to severe weather exhibited statistically significant site-to-site variability. This is to be expected, as some plants, merely because of their geographic location, will tend to have increased exposure to severe weather. Plant-specific estimates were obtained, to the extent possible from the small number of recorded events.

- Analysis of station blackout risk was outside the scope of this study. However, 16 station blackout events were identified during the data review in which a power plant had no AC electrical power from any source for up to one hour. Only two of these events occurred during power operations, and the longest of these two events lasted 11 minutes, which is well below the minimum coping time specified in U.S. NRC Regulatory Guide 1.155. None of these 16 events had the characteristics of a SBO as modeled in NUREG 1032 and most PRAs. That is, the duration of each event was small and the need for accident mitigation system powered from emergency AC power was not present in the events.

- For momentary events, Pilgrim was an outlier, having 8 of the 24 momentary events. Pilgrim was excluded from all industry analyses of momentary events.

The next set of conclusions concerns recovery times:

- For plant-centered events, the events in which the reactor did not trip following the LOSP had longer recovery times than did the trip events and the shutdown events. Therefore, the analysis of recovery times was based on only the trip and shutdown events, which were combined.

- As found by NUREG-1032, the non-momentary recovery times were significantly longer for severe-weather events than for plant-centered events. Too few grid-related events occurred during the period of this report to permit any summary statement about their recovery times.

- NUREG-1032 defined plant design classes I1, I2, and I3, which were believed to have increasing recovery times. No such effect was seen in the 1980-1996 data. The non-momentary recovery times showed no pattern, and the fractions of events that were momentary did not differ much between classes.

ACRONYMS

AC	alternating current
ASP	Accident Sequence Precursor
AEOD	Office for Analysis and Evaluation of Operational Data
EDG	emergency diesel generator
INEEL	Idaho National Engineering and Environmental Laboratory
LER	Licensee Event Report
LOSP	loss of offsite power
MLE	maximum likelihood estimate
NRC	Nuclear Regulatory Commission
NSAC	Nuclear Safety Analysis Center
PRA	probabilistic risk assessment
QA	quality assurance
SCSS	Sequence Coding and Search System
UDI	Utility Data Institute

Evaluation of Loss of Offsite Power Events at Nuclear Power Plants: 1980 - 1996

1. INTRODUCTION

It is recognized that the availability of AC power to commercial nuclear power plants is essential for safe operations and accident recovery. Unavailability of AC power can have a major negative impact on a plant's ability to achieve and maintain a safe shutdown condition. Early probabilistic risk assessment (PRA) studies determined that the loss of AC power can be an important contributor to total risk at nuclear power plants. The United States Nuclear Regulatory Commission (USNRC) initiated a study to estimate the frequency of total loss of offsite power (LOSP), with coincident failure of all on-site AC power sources, based on actual power plant events. That study covered data from 1968 through 1985, and the results were published in NUREG-1032[1] in 1988.

The present report updates a portion of NUREG-1032. One primary objective of this study is to update the LOSP model parameters (frequency and recovery time), based on data from 1980 through 1996. These parameters are needed to determine the risk implications of LOSP and station blackout scenarios, although the determination of such implications is beyond the scope of this study. The present study analyzes events during shutdown, as well as events during power operation, which is beyond the scope of NUREG-1032, which only considered events during operation. The second primary objective of this study is to re-examine the engineering insights from NUREG-1032, using the more recent data. This study does not evaluate emergency diesel generator (EDG) reliability. For such an assessment, see Grant et al.[2] Instead, the present study is restricted to the LOSP events themselves. Table 1.1 summarized the comparison between these three reports.

Table 1.1. Comparison of related reports.

	NUREG – 1032[1]	LOSP Study	Grant, et al.[2]
LOSP at power	1968 - 1985	1980 - 1996	-
LOSP during shutdown	-	1980 - 1996	-
Engineering insights	1968 - 1985	1980 – 1996	-
EDG reliability	1968 - 1985	-	1987 - 1993

The main body of this report contains the scope of the study, a summary of the quantitative results of the analyses, engineering insights, and the major conclusions of the study. The insights include a discussion of possible design features that might affect vulnerability to LOSP. The appendices provide more details about the analysis methods, analyses results, and the data included in the analyses.

2. SCOPE OF STUDY

The scope of this project was to identify LOSP events, to use statistical analysis to characterize the frequencies and recovery times of such events, and to characterize the events from an engineering perspective. The time period considered was January 1980 through December 1996. The study analyzed only events that occurred after a licensee received its full power license so that events early in a plant's learning experience would be excluded.

For this report, LOSP is defined as simultaneous loss of electrical power to all unit safety buses, requiring the emergency power generators to start and supply power to the safety buses. All Class 1E EDGs, the Keowee hydro units at Oconee, and the gas turbine generator at Millstone 1 are considered emergency generators for this study. NUREG-1032 included events that resulted in a loss of power to the non-vital buses as well as the safety buses.

For events that occurred during power operation, this report distinguishes between initiating events and non-initiators. At most plants, LOSP causes the reactor to trip, but some plant designs allow continued operation at power following a complete LOSP event, with the safety buses supplied by the emergency power generators. This report calls the event an initiating event only if the LOSP caused the reactor to trip. Portions of the analysis used only the initiating events, as discussed in Section 2.2 below.

2.1 Data

The operating experience data used in this report are primarily based on Licensee Event Reports (LERs) residing in the Sequence Coding and Search System (SCSS) database. The search criteria initially identified approximately 4500 events involving some electrical failure that occurred from 1980 through 1996. The information encoded in the SCSS database was used only to select LERs to be reviewed for event screening and classification. Engineers that formerly held commercial nuclear power plant senior reactor operator licenses reviewed these 4500 LER abstracts and identified approximately 1400 LERs involving partial or complete losses of offsite power. Information from these LERs was supplemented with the following sources of information to ensure that all appropriate events were included in the study: Nuclear Safety Analysis Center (NSAC)[3] reports, the EDG reliability study,[2] NUREG-1032,[1] the USNRC Office for Analysis and Evaluation of Operational Data (AEOD) Grid Performance report,[4] the Engineering Evaluation of Loss-of-Offsite Power due to Plant-Centered Events (AEOD March 1993),[5] the Accident Sequence Precursor (ASP) database,[6] and the Initiating Event Report.[7] A total of 176 events were identified as meeting the criteria specified for this study (complete LOSP) and coded as LOSP events. Three of these were excluded from the analysis because they occurred before receipt of the full power license. However, those three events were coded and are included in the electronic database.

It should be noted that a loss of offsite power, by itself, does not require a licensee to submit an LER; therefore, some events identified do not have an LER number. Those events without an LER number were identified from review of the above-mentioned comparison data sources.

The time to recovery was defined as the time until offsite power could have been restored by following plant procedures. Often this coincided with the actual reported duration of the LOSP event. Sometimes, however, the LER or the NSAC report stated that offsite power “could have” been restored earlier if it had been needed. If power could have been restored following existing approved procedures, the stated estimated time was entered as the time to recovery. Licensees frequently operate on emergency power sources longer than necessary due to procedural or operational requirements. Engineering judgment had to be used in estimating some recovery times. Also, some event reports gave vague information, so that the recovery time could only be estimated roughly. Finally, the recovery time was completely missing and could not be estimated for some events.

The event data used in the analyses are summarized in Appendix C, along with the operating and shutdown times that were used in the analyses. Appendix C also contains a detailed description of the data coding. Table C-5 lists the plants included in the data analyses.

2.2 Analysis

This report calls the LOSP event an *initiating event* if the loss of offsite power caused the reactor to trip. An event can fail to be an initiating event for two reasons.

- For most plants operating at power, any LOSP event results in a plant trip, or requirement to shut down. The specific design of some plants, however, permits the plant to continue operating at power while the emergency generators supply power to the safety buses. The data set contains such eleven events, when the unit continued to operate throughout the entire loss of offsite power. In general, the result of an LOSP event, trip or not, depends both on the severity of the event and on the design and specifications of the plant.
- In a few cases, the reactor tripped, but the trip preceded the LOSP. Therefore, the LOSP event was not an initiating event.

This distinction between LOSP events and LOSP initiating events pervades the analysis.

A second distinction made is between *momentary* and *non-momentary* events. In about 15% of the LOSP events, offsite power was recovered, or could have been recovered following plant procedures, in less than two minutes. This report calls those events momentary. To characterize the recovery times, the analysis distinguished between momentary and non-momentary events. Therefore, the frequencies are also given separately for the two classes of events.

The LOSP events were grouped into several categories. Following the precedent of NUREG-1032, the events were classified as plant-centered, grid-related, or caused by severe weather. In addition, they were grouped according to whether the plant was operating or shut down. These distinctions were used in the statistical analysis whenever they corresponded to clear differences in the frequencies or recovery times. For plants at power operation, the frequency of LOSP initiating events was estimated from the data. The non-initiators were not used in this estimate, even though those events might have been initiators had they occurred at other plants, or even at those plants under different conditions. For shutdown plants, the frequency of LOSP events was estimated using all shutdown events. That is, the distinction between initiating events and non-initiators was not made for shutdown events; some of the events used might not have caused a trip if they had occurred while the plant was at power. Finally, for each event category, the times to recovery were characterized, ignoring whether the event was an initiating event or not.

Additional analyses were performed to compare the results of this study with the results presented in NUREG-1032. Specific comparisons were for frequency of occurrence, length of recovery time, and the effects of plant design characteristics on LOSP event details.

3. SUMMARY OF QUANTITATIVE RESULTS

This section of the report discusses the results obtained from statistical analyses of the LOSP frequency and recovery time data. For details of the statistical techniques employed, refer to Appendix A. For detailed quantitative results, see Appendix B. This section is organized around the classification scheme developed for NUREG-1032. Thus, the results are presented separately for plant-centered, grid-related, and severe-weather events, in sections 3.1 through 3.3. Since events that occurred during shutdown modes of operation are also included in the present study, some of the results are separated further into operating and shutdown categories. This is beyond the scope of NUREG-1032, which only considered events during power operation. Section 3.4 provides some comparisons with the results of NUREG-1032.

The analysis uses various models, depending on what the data show. For example, frequencies are presented in terms of units (individual power plants), but recovery times in terms of sites. Between-unit or between-site variation is modeled in some cases, and between-year variation in one case. A time trend is always considered, but is modeled only in Section 3.4. The choice of a model is made with care, always based on what the data show. For a full discussion, see Appendices A and B. The diversity of models results from examining diverse data sets. The most appropriate model was used in each case, rather than force-fitting all the data sets into a single model.

3.1 Plant-Centered Events

Per the definition used in NUREG-1032, plant-centered events are those "in which the design and operational characteristics of the plant itself play the major role in the cause and duration of the loss of offsite power." Plant-centered failures typically involve hardware failures, design deficiencies, human errors, and localized weather-induced faults such as lightning.

NUREG-1032 found that such plant-centered events accounted for the majority of the losses of offsite power. The current study supports that finding, with plant-centered events dominating the LOSP frequency during power operation and during shutdown. The events used in the analysis are listed in Table C-1 of Appendix C. They are summarized in Table C-5 of Appendix C.

3.1.1 Frequency During Power Operation

The frequency of plant-centered initiating events was clearly smaller during power operation than the frequency of LOSP events during shutdown (see section B-1 of Appendix B). This was true both for momentary and non-momentary events. Engineering reasons for this are discussed in section 4. Therefore, the results for the two plant conditions are presented separately here and in section 3.1.2. Table 3.1 below summarizes the results of the initiating events during power operation. Critical hours for 1980 were estimated. The source of the outage and critical times for 1981 - 1996 is discussed more fully in section A-1.3 of Appendix A.

Table 3.1. Summary statistics on frequencies: plant-centered LOSP initiating events during power operation.

Number of unit initiating events (= momentary + non-momentary)	50 (= 4 + 46)
Number of non-initiators (LOSP events at power when reactor did not trip, or tripped just before LOSP)	15
Total unit-years of criticality (critical time is estimated for 1980)	1188.6
Frequency of initiating events (= frequency for momentary events + frequency for non-momentary events)	0.04 per unit critical year (= 0.003 + 0.039)
90% uncertainty interval on frequency of non-momentary events. (This is not a simple confidence interval, but instead accounts for the large observed variation from year to year.)	0.006 to 0.1
Minimum and maximum number of initiating events at any plant	0, 3
No. of units with 0, 1, 2, and 3 initiating events, respectively	74, 35, 6, 1
Average number of initiating events per unit	0.43

LOSP, per the definition established for this study, results in a loss of power to all safety (vital) buses and a signal for all available emergency AC generators to start and power their respective buses. This definition is slightly different from the one established for NUREG-1032, in that NUREG-1032 also included events that resulted in loss of power to the non-vital buses. The event is an *initiating event* if, in addition, a reactor trip results. Of the 65 plant-centered LOSP events at power, 11 were not initiating events because the reactor remained at power. Four others were not initiating events because the trip preceded, and caused, the LOSP. Following the precedent of NUREG-1032, frequencies are estimated only for initiating events.

No statistically significant plant-to-plant variability was found in the frequency of plant-centered LOSP initiating events during operation; whatever variability exists is too small to be clearly evident in the 17 years of data. When we attempted to account for it anyway, the resulting model was degenerate, assigning the same frequency to every unit.

Figure 3.1 shows that the slight downward trend in time was not statistically significant. However, significant year-to-year variability was seen, beyond what is expected under the usual Poisson model. A partial explanation of this extra-Poisson scatter is dependence between units — in several cases a single site event caused simultaneous LOSP at both units of the site. This dependence increases the variability in the annual count of events. Therefore, a single generic estimate was found, with an uncertainty that accounts for the extra-Poisson variation. Table B-3, Appendix B, presents the corresponding gamma distribution, which can be used for a PRA at a particular plant. No effect was found in the data that could be related directly to the Station Blackout Rule (10 CFR 50.63), which was published in June 1988.
talk about weak eng. basis for believing in a trend?

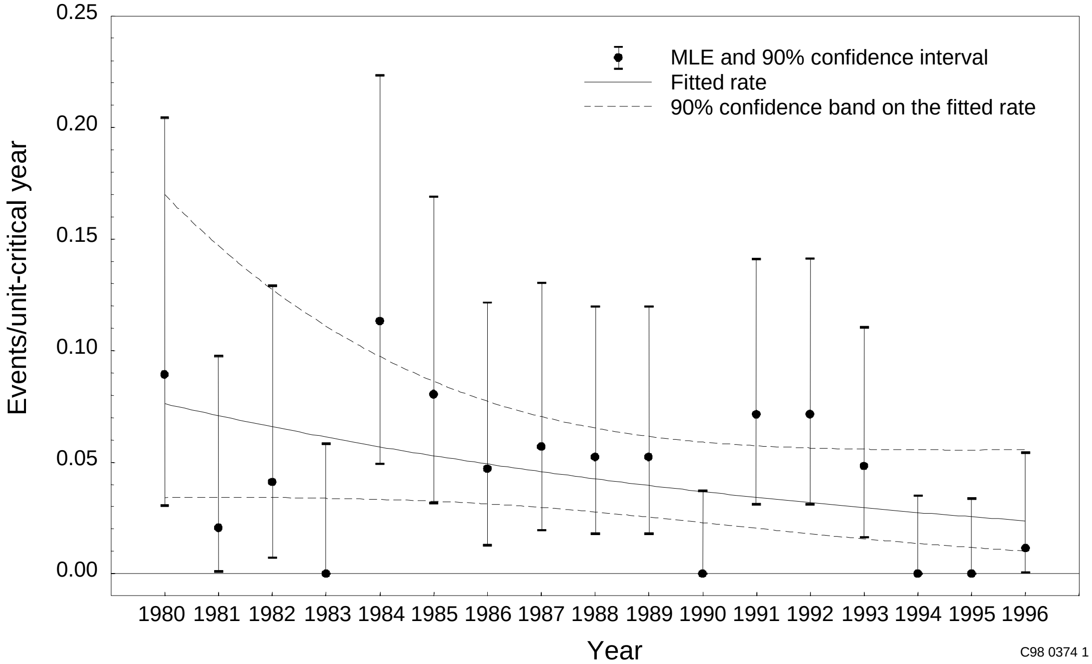

Figure 3.1. Frequency of plant-centered LOSP non-momentary initiating events during operation. When the extra-Poisson scatter is accounted for, the trend is not statistically significant (p-value = 0.11).

3.1.2 Frequency of LOSP Events During Shutdown

Although NUREG-1032 did not examine events that occurred in non-power modes of operation, this study includes analyses of the shutdown events. The definition of LOSP is the same as that used above for power operation, but now the issue of initiating events does not arise: any loss of power to all safety buses that challenged the emergency power sources is counted, whether or not it would have caused a trip from power at that particular plant.

Table 3.2 summarizes the results for plant-centered events that occurred while the reactor was shut down.

The frequency of plant-centered events is significantly higher during shutdown than during power operation. Section 4 discusses possible engineering reasons for this. Unlike events that occur with the plant at power, there is statistically significant variability in the LOSP frequency from one plant to another during shutdown. The analysis method used for this study accounts for this variability, as discussed below. Variability between years was not modeled because it was not statistically significant.

Table 3.2. Summary statistics on frequencies: plant-centered LOSP events during shutdown.

Number of unit events (= momentary + non-momentary)	80 (= 11 + 69)
Total plant shutdown years (shutdown time is estimated for 1980)	455.7
Frequency of events (= frequency for momentary events + frequency for non-momentary events). However, the final analysis of momentary events excludes Pilgrim as an outlier.	0.18 per plant shutdown year (= 0.024 + 0.151)
90% uncertainty interval on frequency of non-momentary events (This is not a simple confidence interval, but instead accounts for the large observed variation among plants.)	0.01 to 0.54
Minimum and maximum number of events at any plant	0, 5
No. of units with 0, 1, 2, 3, 4, 5 events, respectively	69, 27, 13, 3, 2, 2
Average number of events per plant	0.69

Using the methods explained in Appendix A, the population variability for non-momentary events was modeled by a gamma distribution, with shape parameter equal to 1.13 and scale parameter equal to 7.13 years (see Table B-3 of Appendix B). This gives a prior mean frequency of 0.16 per plant shutdown year, essentially the same as the simple estimate 69/455.7. The distribution has a 5th percentile of 0.01 per plant shutdown year and a 95th percentile of 0.45 per plant shutdown year.

This distribution was used to update each plant's specific data, yielding a wide range of posterior mean frequencies. The smallest was 0.05/plant-shutdown-year (90% interval from 0.003 to 0.16) at Browns Ferry 1, which experienced no events in about 13.5 shutdown years. The largest was 0.5/plant-shutdown-year (90% interval from 0.2 to 1.1) at La Crosse, which experienced 4 non-momentary events in approximately 2.3 shutdown years. The plant-specific frequencies are given in Table B-3 of Appendix B.

No statistically significant trend was seen in the frequency of plant-centered shutdown events over time. This is illustrated in Figure 3.2 below.

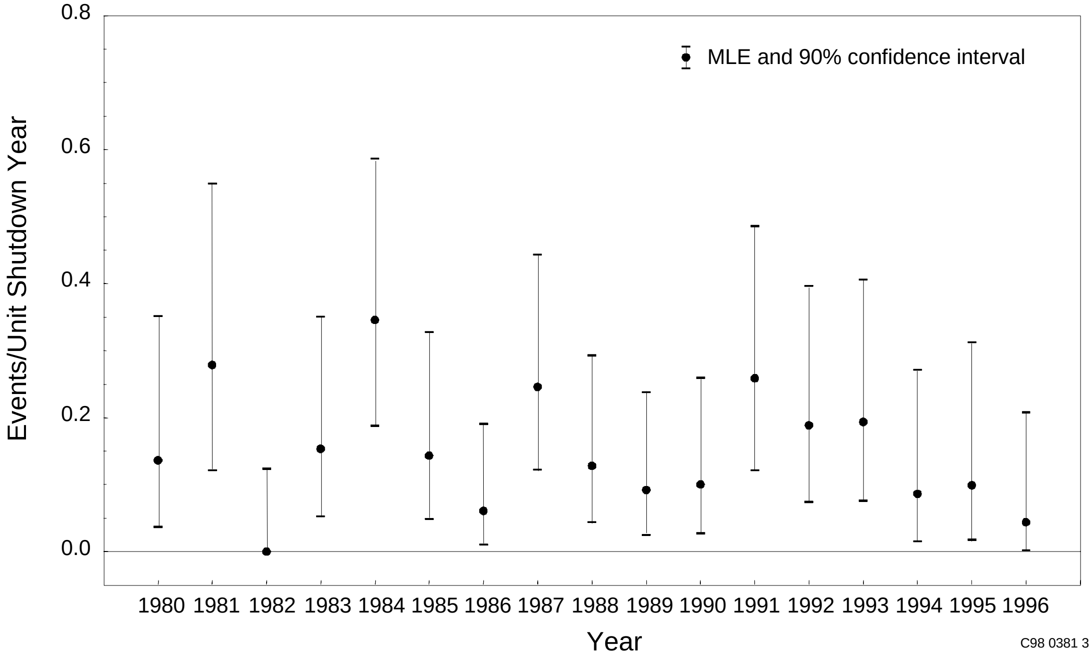

Figure 3.2. Frequency of plant-centered LOSP non-momentary events during shutdown. No trend is fitted, because it is not close to statistically significant. Between-unit variation is present, but the confidence intervals for each year ignore this.

3.1.3 Time to Recovery

The non-momentary recovery times during power and during shutdown did not differ by a statistically significant amount, as shown in Section B-3.1, of Appendix B. Therefore, the events at power and during shutdown were all analyzed together. The few events for which the trip preceded LOSP were combined with the other events, because the recovery times appeared similar. For the events at power, only the trip events were used, because the recovery times when the unit continued operating were significantly longer. A possible explanation of this last observation is that the unit personnel will tend to act very carefully and deliberately when the plant is operating on emergency power, to prevent a trip.

When a single event caused LOSP at more than one unit at a multiple-unit site, the recovery times were typically similar or identical. Therefore, the recovery times were averaged, and the analysis was by site event rather than by plant event. Table 3.3 summarizes the results.

Table 3.3. Summary statistics on times to recovery: plant-centered LOSP trip or shutdown events with recovery times ≥ 2 minutes.

Number of events with reported recovery times, by site	102
Number of events with no reported recovery times, by site	9
Mean time to recovery	85.4 min.
Median time to recovery	29 min.
Minimum and maximum times	2 min., 1675 min.
90% uncertainty interval on time to recovery (based on fitting a lognormal distribution to the recovery times)	2.8 to 314 min.

Figure 3.3 below shows a histogram of the recovery times.

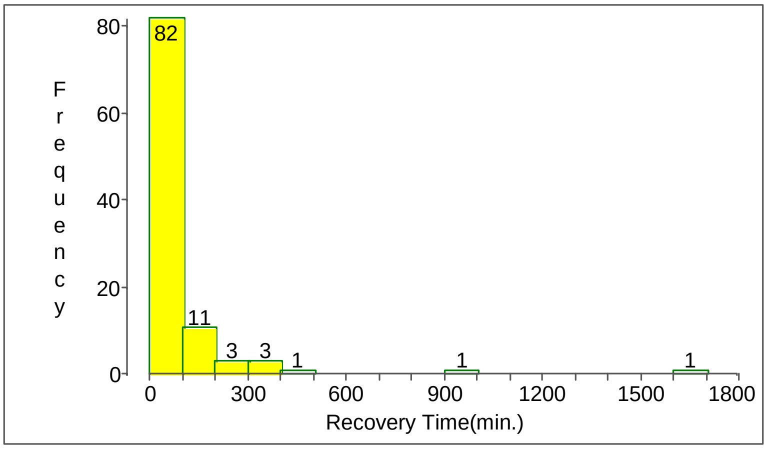

Figure 3.3. Histogram showing recovery times (minutes) for plant-centered trip and shutdown events with recovery times ≥ 2 minutes. This plot does not show 11 events with very short recovery times and 9 events with unknown recovery times.

A lognormal distribution fit the recovery times well. The fitted mean and standard deviation of ln(recovery time) were $\mu = 3.39$ and $\sigma = 1.435$. Percentiles of this lognormal distribution are given in Table B-8 of Appendix B. Figure B-18 in Appendix B shows the fitted survival curve and the empirical survival curve.

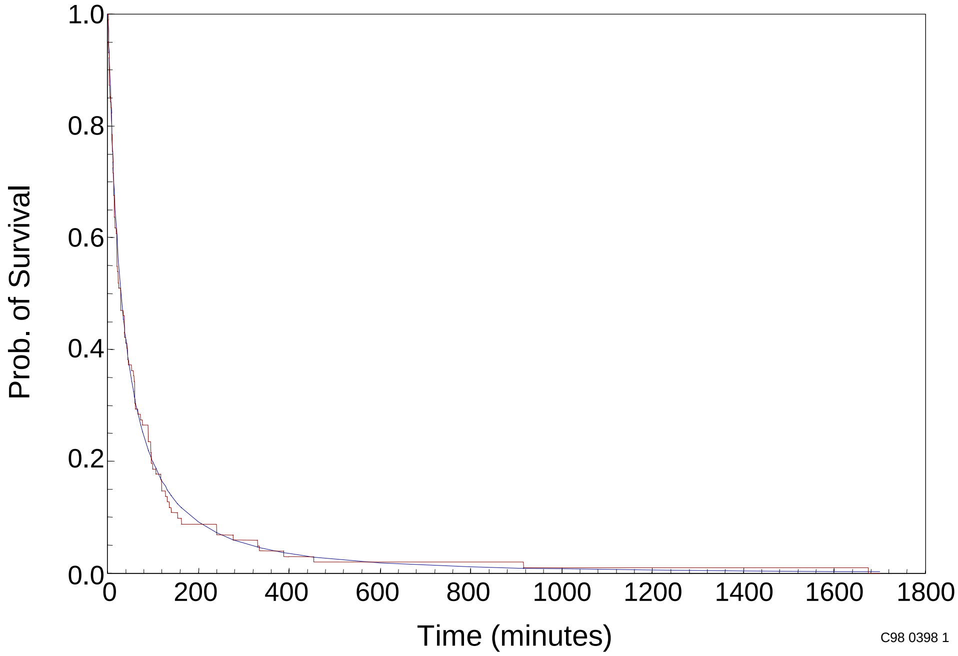

Figure 3.4. Survival curves for recovery time (minutes) of plant-centered non-momentary trip events, empirical and fitted lognormal (median 29.6, error factor 10.6).

Appendix B compares recovery times during power operation with recovery times for events that occur during shutdown. No clear differences can be found between the causes (human error, equipment problem, external environment) or between the shutdown and trip events, for the non-momentary recovery times.

For the momentary events, on the other hand, the shutdown events are dominated by human error (6 of 8 events), and the trip events are dominated by equipment failures (5 of 6 events). Pilgrim, an outlier for momentary events, is excluded from these counts.

3.2 Grid-Related Events

Grid-related events are those in which problems in the offsite power grid cause the LOSP and impact its duration. There were only six such events from 1980 to 1996. They are listed in Table C-2 of Appendix C, and listed more briefly here in Table 3.4. Appendix C explains the meanings of the column headings, which are also the LOSP database field names.

Table 3.4. Grid-related LOSP events.

LER	Plant Name	Event Date	Status	Cause	Initiator	Recovery Time (min)
25185011	Turkey Point 3	05/17/85	S	Fire	1	156
25185011	Turkey Point 4	05/17/85	T	Fire	1	125
31281034	Rancho Seco	06/19/81	S*	Load (brownout)	1	360
31281039	Rancho Seco	08/07/81	S*	Load (brownout)	1	180
33184028	Duane Arnold	07/14/84	T*	Equip	1	1.0
39589012	Summer	07/11/89	T*	Equip	0	130

Each event has unique characteristics: the Turkey Point events constituted a single site event; the Rancho Seco events may be dependent; the Duane Arnold event was a momentary event; in the Summer event a plant trip caused the grid disturbance and the subsequent LOSP. This uniqueness, and the small number of events identified during the data review, make it difficult to perform any meaningful statistical analysis. Therefore no statistical analysis is presented here, although a few summaries are given in Appendix B.

As discussed in Section 4.1.2 below, grid-related LOSP events have become rare. None have occurred in the 1990s. Only the Turkey Point events, which are both from one initiating event, were total losses of all AC power to a plant/site from grid-related causes during the time period 1980 through 1996.

3.3 Severe-Weather Events

Severe weather is defined to be weather with forceful and non-localized effects. This is the same as the NUREG-1032 use of the term. A loss of offsite power was classified as a severe-weather event if the weather was widespread, not just centered on the plant, and capable of major disruption. An example is storm damage to transmission lines, as opposed to debris blown into a transformer. This does not mean that the event actually resulted in widespread damage, as long as the potential was there. For example, a tornado might affect one plant unit and miss the other. Because of a tornado's potential to affect both units, it would still be counted as a severe-weather event. Lightning strikes, though forceful, are normally localized to one plant, and thus coded as plant-centered, as they were in NUREG-1032. Examples of severe weather include hurricanes, tornadoes, snow, and ice storms. The frequency of LOSP from such events is lower than from plant-centered causes, but the recovery time, for non-momentary events, is typically longer. The events included in the analysis are listed in Table C-3 and are summarized in Table C-5 of Appendix C.

3.3.1 Frequency During Power Operation

The frequency of severe-weather initiating events was determined to be marginally smaller during power operation than the frequency of severe-weather LOSP events during shutdown (see section B-1 of Appendix B). In addition, between-unit variation was seen for shutdown events, but none at all was seen for initiating events. For these reasons, and for consistency with the presentation of plant-centered events, the results for the two plant conditions are presented separately here and in Section 3.3.2. Differences exist between sites, and therefore also between units. The between-unit variability was modeled, as discussed below, rather than the between-site variability. The main reason for this is the conceptual difficulty in defining a site-critical year and a site-shutdown year. This is discussed more fully in Section A-1.5.3 of Appendix A.

Sometimes, a unit had shut down in anticipation of a major storm. In such a case, if LOSP occurred, the event was classified as Trip*, not as Shutdown. Therefore, the practice of shutting down in anticipation of storms does not lead to an overestimate of the shutdown event frequency.

Table 3.5 below summarizes the results of the initiating events during power operation.

Table 3.5. Summary statistics on frequencies: severe-weather LOSP initiating events during power operation.

Number of unit initiating events (= momentary + non-momentary)	11 (= 4 + 7)
Number of non-initiators (LOSP events at power when reactor did not trip, or tripped just before LOSP)	0
Total plant-years of criticality (critical time is estimated for 1980)	1188.6
Frequency of initiating events (not broken into momentary and non-momentary components, because 2 of the 4 momentary events were at one unit, Pilgrim)	0.009 per plant critical year
90% confidence interval on frequency of non-momentary events	0.003 to 0.01
Minimum and maximum number of initiating events at any plant	0, 3
No. of units with 0, 1, 2, and 3 initiating events, respectively (Pilgrim is the unit with 3 events, 2 of which were momentary)	107, 8, 0 , 1
Average number of initiating events per unit	0.09

When the non-momentary events were analyzed, no variation could be modeled between units. Similarly, when the momentary events were modeled and Pilgrim was excluded, no variation could be modeled between units. Variability between years was insignificant and was not modeled. The final results are given in Table B-3 of Appendix B.

3.3.2. Frequency During Shutdown

Table 3.6 summarizes the results for severe-weather events that occur while the reactor is shut down.

Table 3.6. Summary statistics on frequencies: severe-weather LOSP events during shutdown.

Number of unit events (= momentary + non-momentary)	11 (= 4 + 7)
Total plant shutdown years (shutdown time is estimated for 1980)	455.7
Frequency of events (not broken into momentary and non-momentary components, because 3 of the 4 momentary events were at one unit, Pilgrim)	0.02 per plant shutdown year
90% confidence interval on frequency of non-momentary events	0.007 to 0.03
Minimum and maximum number of events at any unit	0, 4
No. of units with 0, 1, 2, 3, 4 events, respectively	110, 4, 0, 1, 1
Average number of events per unit	0.09

The frequency of severe-weather non-momentary events is higher during shutdown than during power operation, as was also the case for plant-centered events. However, it is difficult to say whether the difference is statistically significant, for reasons discussed in Appendix B. Just as for severe-weather events during power operation, there is statistically significant variability in the LOSP event frequency from one plant to another during shutdown. The analysis method is the same as in sections 3.1.2.

For non-momentary events, the population variability was modeled by a gamma distribution, with shape parameter equal to 0.126 and scale parameter equal to 8.88 shutdown years (see Table B-3 of Appendix B). This gives a prior mean frequency of 0.014 per plant shutdown year, essentially the same as the simple estimate 7/455.7 = 0.015. The distribution has a 5th percentile of <1.E−10 per plant shutdown year and a 95th percentile of 0.08 per plant shutdown year. The 5th percentile is very small, and the value depends strongly on the use of a gamma distribution to model the between-plant variability.

This distribution was used to update each plant's specific data, yielding a wide range of posterior mean frequencies. The smallest was 0.006/plant-shutdown-year (90% interval from <1.E−10 to 0.03) at Browns Ferry 1, which experienced no events in about 13.5 shutdown years. The largest was 0.2/plant-shutdown-year (90% interval from 0.02 to 0.6) at Crystal River 3, which experienced 3 non-momentary events in approximately 5.2 shutdown years.

No statistically significant time trend was seen in the frequency of severe-weather shutdown events, although the year 1993 had a high number of events because of a single storm that affected much of the East Coast. A plot by year is given in Figure B-8 of Appendix B. The variation between years was statistically significant, because of the year 1993. However, plant-specific estimates are much more interesting than year-specific estimates. Therefore, only the between-unit variation was modeled. The data set was much too sparse to allow modeling of both.

3.3.3 Time to Recovery

Because the weather-related non-momentary recovery times did not differ significantly between power operation and shutdown, they are analyzed together here. As throughout this report, when a single event caused LOSP at more than one unit, the recovery times were typically similar or identical. Therefore, the recovery times were averaged, and the analysis is by site event rather than by plant event. The results are summarized in Table 3.7 and in Figure 3.5.

Table 3.7. Summary statistics on times to recovery: severe-weather LOSP events with recovery times ≥ 2 minutes.

Number of site events with reported recovery times	9
Number of site events with no reported recovery times	1
Mean time to recovery	1258 min.
Median time to recovery	270.5 min.
Minimum and maximum times	37 min., 7929 min.
90% uncertainty interval on time to recovery (based on modeling lognormal components of variance for the recovery times)	23 to 5009 min.

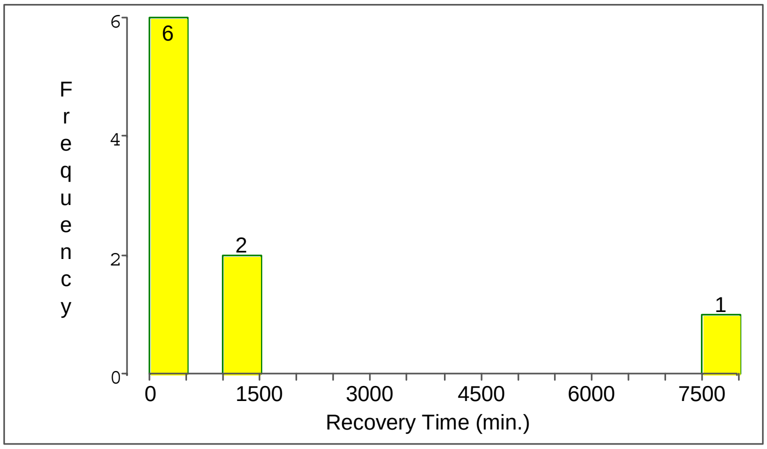

Figure 3.5. Histogram of recovery times (minutes) for non-momentary severe-weather LOSP events. For any event, the recovery times have been averaged for multiple units at a site, and regarded as a single time.

The variability among observed recovery times is very large, from 37 seconds to over 5 days. As discussed in section B-4.2, the between-site variance is smaller than the between-event variance, and calculations of statistical significance are hampered by the small size of the data set. When site-specific estimates were found, they overlapped greatly. Therefore, any between-site differences were ignored, and only a single generic distribution is presented, given in Table B-8 of Appendix B.

3.4 Comparisons with NUREG-1032

NUREG-1032 considers events from 1968 through 1985, partly overlapping the time span of this report. Although the analysis methods are somewhat different in the two reports, the overall conclusions can be compared.

3.4.1 Plant-Centered Events

NUREG-1032 only considers plant-centered initiating events that occurred during power operation. Therefore, the plant-centered shutdown events in this report cannot be compared to results from NUREG-1032. The following comparisons can be made, based on section 3.1 of this report and Table 3.1 of NUREG-1032.

Table 3.8. Plant-centered events in NUREG-1032 and present study.

	NUREG-1032	Present Study
	Frequency of Initiators	
Number of initiators	46 site initiating events	50 plant initiating events
Number of years	527 reactor critical site years	1189 reactor critical plant years
Estimated frequency	0.09 per site critical year	0.04 per plant critical year
	Time to Recovery	
Number of reported times, for site events	46	118 (trip and shutdown events, momentary and non-momentary)
Median recovery time	18 minutes	20 minutes

Thus, the superficial comparison is that plant-centered LOSP initiators have become less frequent but that they last about the same time. As discussed below, the change in estimated frequencies can be attributed to real changes in the plant operating histories.

Frequencies. To compare the frequencies over the combined time period of NUREG-1032 and the present study, plant calendar years were used, because plant operating data are uncertain and incomplete before 1981. As described in section B-5.1 of Appendix B, unit calendar years were available from 1969 on. LOSP events from 1969 through 1979 were obtained from Table A.4 of NUREG-1032. Table B-9 in appendix B displays the data used in the analyses. Figure 3.6 shows the trend. It confirms the above conclusion that plant-centered initiating events have become less frequent. The trend is statistically significant (p-value = 0.0001), and the fit is acceptable. The fraction of time when reactors are critical has increased since the late 1980s. Thus, the decreasing trend would appear slightly more pronounced if critical time were used instead of calendar time.

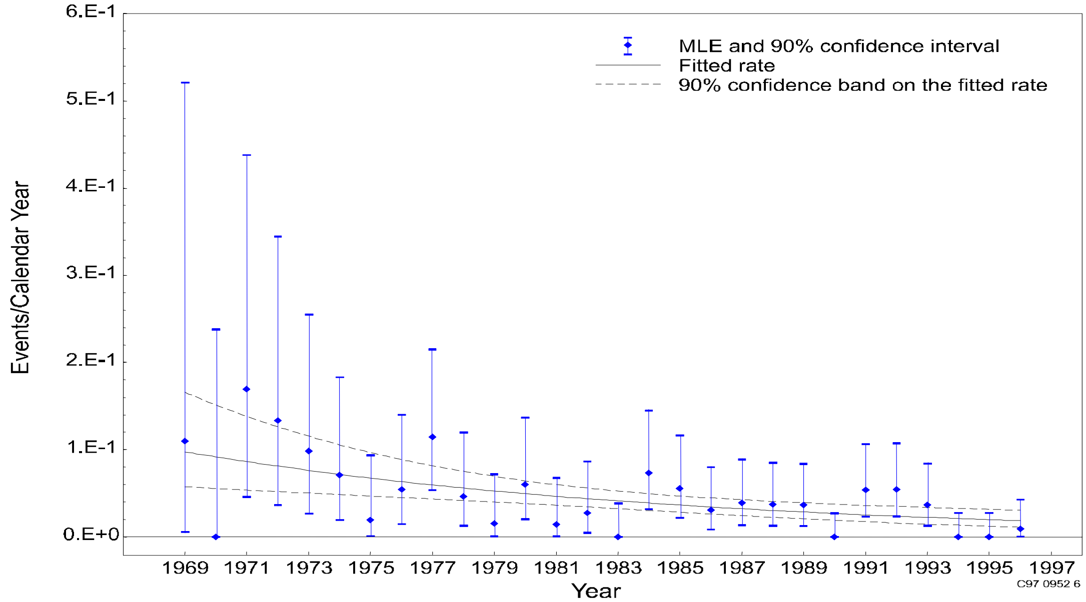

Figure 3.6. Frequency of plant-centered LOSP initiating events per unit year. The trend is statistically significant.

The present study includes 18 plant-centered initiating events in the 1980-1985 period, while 16 are listed in Table A.1 of NUREG-1032. Twelve events are included in both studies, and the other four from NUREG-1032 are classified as shutdown events using the criteria for the current study. This suggests that the present study is at least as complete as NUREG-1032. Therefore, the decreased frequency noted above apparently is not a result of incomplete data counts.

Recovery Times. Any investigation of recovery times is complicated by the need for judgment in assessing when offsite power could have been restored following plant procedures. The practice in recent years, especially during trip events, has been to run on emergency power longer than absolutely necessary, because other actions have a higher priority while shutting down the reactor. Therefore, more judgment is called for in assessing recent recovery times than may have been required before the mid-1980s.

Figure 3.7 shows the values of $\log_{10}$(recovery time) used in the present study, plotted by date. It is not easy to say whether a trend is present. The longest recovery time, in the upper right corner, is an actual recovery time, and based on the narrative, offsite power may have been restorable earlier. This illustrates the difficulty in determining when power could have been restored. The statistical significance of any trend is highly dependent on the two upper right points. No trend is modeled in the analysis of this report. *Frances and Dave, shall we just drop the discussion of recovery times here? Table 3.8 doesn't raise the issue.*

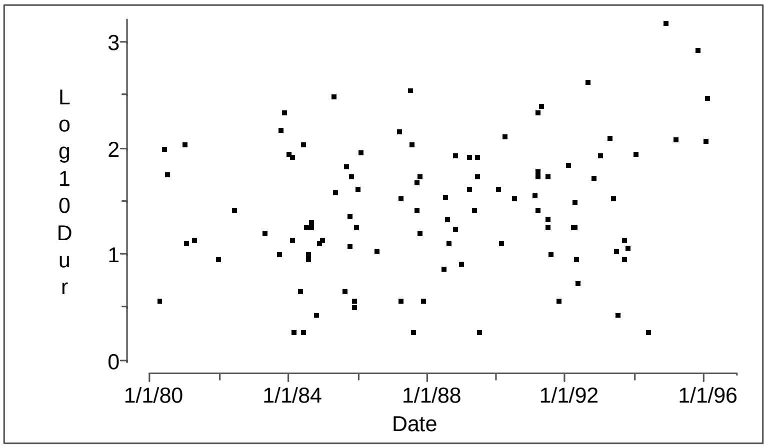

Figure 3.7. For non-momentary plant-centered events, plot of $\log_{10}$(recovery time) against event date. A slight upward trend is statistically significant (p-value = 0.03), but is highly dependent on the two points in the upper right, as discussed in the text.

3.4.2 Grid-Related Events

Table 3.9 gives a summary comparison between the findings of NUREG-1032 and the present report.

The table shows that the frequency of grid-related initiating events has dropped by an order of magnitude between the study period of NUREG-1032 and the present study period. If the usual assumption of independence can be applied to the NUREG-1032 data, the difference is statistically very significant. The difference is also consistent with the fact that none of the grid-related events for the present study occurred in the 1990s. The recovery times for the present study tend to be longer, but the data set is quite small.

Table 3.9. Grid-related events in NUREG-1032 and present study.

	NUREG-1032	Present Study
	Frequency of Grid-Related Initiating Events	
Number of initiators	12 site initiating events	2 site initiating events
Number of site years	664 site calendar years	1065 site calendar years
Estimated frequency of initiating events	0.018 per site calendar year	0.0019 per site calendar year
	Time to Recovery	
Number of reported times for site events	12	5 (initiating and non-initiators, momentary and non-momentary)
Median recovery time	36 minutes	140.5 Minutes

3.4.3 Severe-Weather Events

Table 3.10 gives a summary comparison between the findings of NUREG-1032 and the present report. The differences between the two studies appear minor, explainable by the small size of the data sets and the great variability among recovery times for different events.

Table 3.10. Severe-weather events in NUREG-1032 and present study.

	NUREG-1032	Present Study
	Frequency of Severe-Weather Initiating Events	
Number of initiators	6 site initiating events	7 site initiating events
Number of site years	664 site calendar years	1065 site calendar years
Estimated frequency of initiating events	0.009 per site calendar year	0.0066 per site calendar year
	Time to Recovery	
Number of reported times for site events	6	16 (initiating and non-initiators, momentary and non-momentary)
		11 if Pilgrim momentary events are excluded
Median recovery time	4.5 hours	1.2 hours, based on all 16 events 2.4 hours, excluding Pilgrim momentary events
	3.5 hrs. from modeling Weibull distribution	3.4 hours, excluding Pilgrim momentary events and combining models for momentary and non-momentary initiating events (see text)

The final median, based on modeling the momentary and non-momentary events, was found as follows. The Pilgrim momentary events were excluded. There were then 5 initiating site events, of which 4 were non-momentary. The non-momentary recovery times were modeled as lognormally distributed, with median 341 minutes and error factor 14.7, from Table B-8. The 37.5th percentile of this distribution is 202 minutes (= 3.4 hrs). Therefore, the probability that a recovery time is greater than 202 minutes equals

$$
\begin{aligned}
\text{Prob(time} > 202) &= \text{Prob(time} > 202 \mid \text{event is non-momentary)} \times \text{Prob(event is non-momentary)} \\
&= (1 - 0.375) \times (4/5) \\
&= 0.5 \ .
\end{aligned}
$$

3.4.4 Complementary Cumulative Frequency Curves

Figure 3.8, from NUREG-1032, shows complementary cumulative frequency curves. For any time *t*, in hours, the height of the curve at *t* is the frequency of events with recovery times exceeding *t*. Because each curve was generated by fitting a parametric distribution to a portion of the data, the curve labeled 'Total' is not the exact sum of the three other curves. This is especially visible in the region around 3 hours, where the Total curve is about twice as high as the sum of the other three.

For comparison, Figure 3.9 shows the complementary cumulative frequency curves from the 1980-1996 initiating event data. Figure 3.9 uses the empirical step functions, with a jump at each observed duration. By definition, the 'Total' curve is the sum of the other three. Other than that minor difference in technique, the two figures are comparable.

There are two notable differences between the two figures. First, in Figure 3.9, the curve for grid-related events is much lower than in Figure 3.8, and is virtually negligible as a contribution to the total frequency of occurrence. Second, there are fewer short events (shorter than one half hour) and about the same number of long events (longer than three hours) in the present study, represented by Figure 3.9. These observations are consistent with those of sections 3.4.1 and 3.4.2.

Figure 3.9 only includes initiating events during power operation, to allow direct comparison with NUREG-1032 results. Recall that for the current study the recovery times were similar for events during shutdown and operation (section 3.1.3), and that slightly more events occurred during shutdown than during operation (sections 3.1.1 and 3.1.2). Therefore, if *all* events had been included in Figure 3.9, the curves would be roughly twice as high as in Figure 3.9, but the qualitative relationship between the curves would remain similar to Figure 3.9.

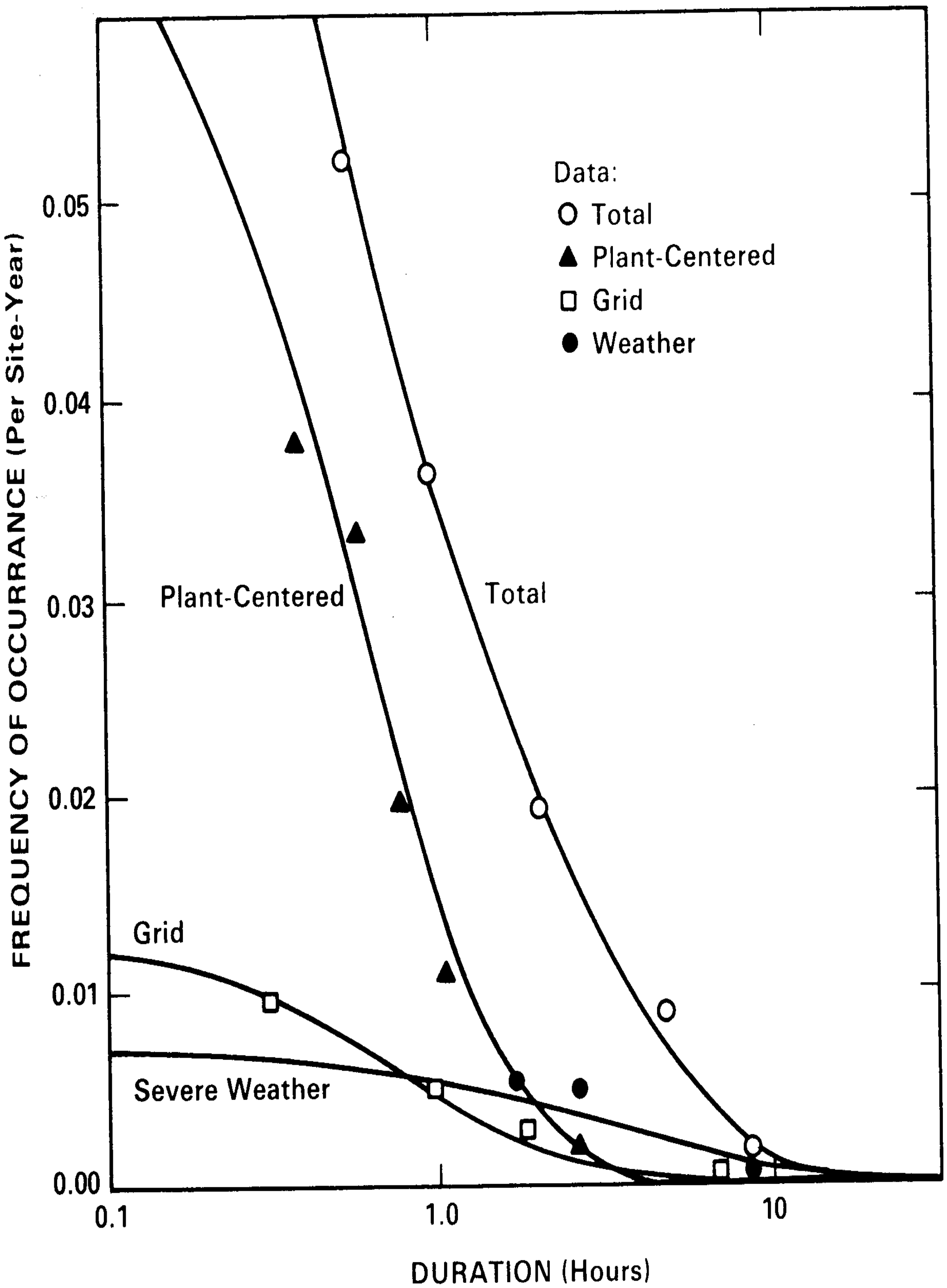

Figure 3.8. Cumulative frequency curves, from NUREG-1032. Height of curve equals frequency of exceeding the time on the horizontal axis.

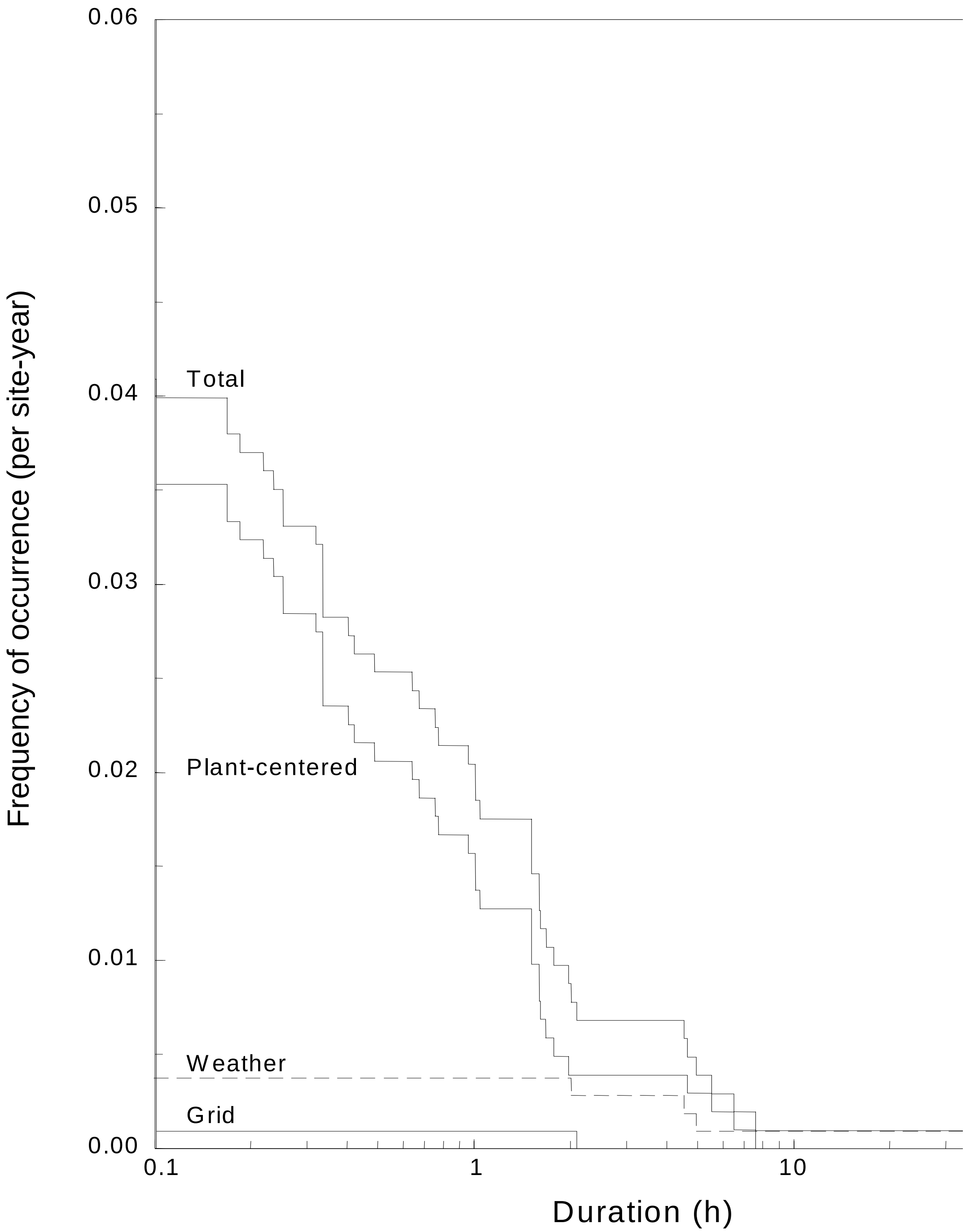

Figure 3.9. Complementary cumulative frequency curves using 1980-1996 initiating event data. Interpretation is the same as for Figure 3.8. As discussed in the text, the recovery times have not been systematically reviewed.

3.4.5 Relationship between Recovery Time and Plant Design

NUREG-1032 defined three groups of plants, denoted as I1, I2, and I3. This classification is based on various design factors concerning offsite power sources and the existence of automatic transfer mechanisms. The design features of I3 plants are either no fast transfer to another offsite power source or no independence in the fast transfer source, in combination with limited or no independence of the incoming power lines. The I1 plants are designed to automatically transfer to another offsite power source, and if that source fails there is yet another transfer to another offsite power source. For details of these groupings and design features, refer to NUREG-1032, Tables A.2 and A.3. Table C-6 of Appendix C displays the plant classifications used in this study.

Figures 3.10 and 3.11 show that the non-momentary recovery times show no statistically significant relation to design group.

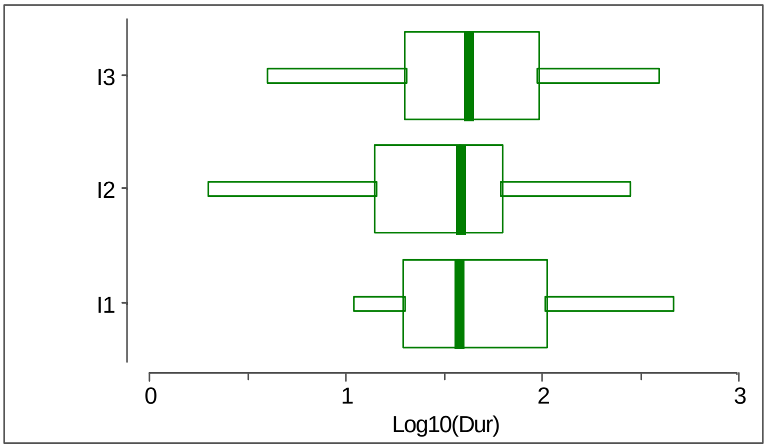

Figure 3.10. Log_{10}(recovery time), for plant-centered trip events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.39).

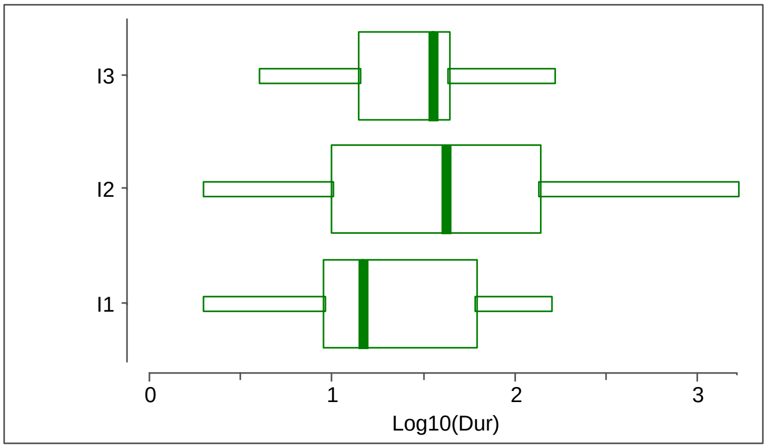

Figure 3.11. Log_{10}(recovery time), for plant-centered shutdown events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.37). The difference between groups I1 and I3 is also not statistically significant (p-value = 0.35).

The design groups correspond to capability for fast transfer. Therefore, one might suppose that any difference among the design groups might be revealed in the momentary events rather than the non-momentary events. Table 3.11 shows that this also is not the case. Note in particular that the confidence intervals overlap greatly.

Table 3.11. Estimated probability that a random LOSP event is momentary.

Design Group	Momentary Events	All Events	Observed Fraction of Momentary Events	90%Confidence Interval on Prob(event is momentary)
Trip Events (p-value for difference between design groups = 0.46)				
I1	0	9	0.0	(0.00, 0.28)
I2	5	33	0.15	(0.06, 0.29)
I3	2	11	0.12	(0.02, 0.33)
Shutdown Events (p-value for difference between design groups = 0.40)				
I1	1	20	0.05	(0.003, 0.22)
I4	4	42	0.10	(0.03, 0.21)
I3	4	23	0.17	(0.06, 0.36)

I suggest that we drop the next section. It doesn't seem worth the trouble to recalculate the numbers, given what is shown above. - Cory

Table 3.12 summarizes the recovery times of plant-centered LOSP events in this study and in NUREG-1032, by design group. For this study, the events considered occurred during both shutdown and power operation, and not all those during power operation were initiating events. For NUREG-1032, most of the events considered occurred during power operation and were initiating events. The qualitative results of the recovery time analysis for the three design groups are the same in the two reports, as shown in Figure 3.10. The times tend to be longer in this report than in NUREG-1032, as discussed in sections 3.4.1 and 3.4.1.2.

Table 3.12. Summary of recovery times for all plant-centered events included in this study and in NUREG-1032.

	I1	I2	I3
Present Study, Shutdown Events			
N	17	24	22
Median time to recovery	10 min.	20.5 min.	34 min.
Mean time to recovery	20 min.	93 min.	99 min.
Present Study, Initiating Events			
N	7	23	14
Median time to recovery	57 min.	38 min.	44.5 min.
Mean time to recovery	110 min.	89 min.	141 min.
Present Study, All Events			
N[a]	28	51	38

Median time to recovery	13 min.	24 min.	36 min.
Mean time to recovery	53 min.	99.5 min.	146 min.[b]
NUREG-1032 (Initiating Events)			
N	14	13	13
Mean time to recovery	12 min.	23 min.	47 min.

a. These numbers do not equal the sum of the counts above, because they include 12 non-initiating events at power, and because in two cases a unit shutdown event and a unit operating event are combined into a single site event.

b. This mean is larger than the two means above, because it includes a non-initiating event at power with a long recovery time.

4. ENGINEERING INSIGHTS

This section of the report discusses the results presented in section 3 from an engineering perspective. The objective of this part of the study is to attempt to provide some insight into the quantitative results, and what plant designs or operating activities might impact either the LOSP frequencies or recovery times. The insights presented here are not the result of qualitative studies performed independently of the quantitative analyses, but are intended to complement the findings presented in section 3.

4.1 Events by Frequency

4.1.1 Plant-Centered Events

This is the largest group of events resulting in a loss of offsite power, accounting for approximately 80% of all events. Although the total of plant outage years (shutdown) are only roughly a third of the total plant operating years, the number of plant-centered LOSP events while shutdown is approximately 50% higher than while operating. (Details of this are displayed in Figure B-1 in Appendix B.) This is an expected result because shutdown plant conditions typically involve more vulnerable electrical plant configurations due to testing and maintenance activities. In addition, less redundancy in offsite power supplies is required by Technical Specifications while a plant is in a shutdown condition. Therefore a plant may, and often does, have fewer incoming power feeds to its shutdown electrical line-up. For example, at Haddam Neck (LER 21393009), a testing line-up placed all shutdown power through a single incoming electrical line. The wrong breaker opened during the test because of a wiring error, and all internal plant power was lost. A plant in a similar situation could experience an otherwise minor event resulting in a complete power loss that would have only been a partial loss of offsite power if all redundant electrical equipment had been operable.

4.1.2 Grid-Related Events

Because the power grid is not affected by whether a power plant is operating or in a shutdown condition (assuming a steady state condition, i.e., no transient that will cause grid fluctuations), all grid-related events were considered together for the engineering analysis.

The nature and small number of grid-related events indicates that losses of offsite power to a nuclear power plant due to grid disturbances are rare events and none have occurred in the 1990s. Of the six events identified in the study, two of them, at Rancho Seco, were actually electrical brownout situations, both occurring in the summer of 1981. It is suspected, but not proven, that these two events were not independent, due to the short time between the events and the similarity of the occurrences. Both the Summer event (not used for frequency analysis) and the Duane Arnold event did not involve loss of power to all plant buses; only the safety buses were affected by the grid voltage degradation. The Turkey Point events resulted from the same brush fire and thus both events are from the same initiator, implying only one natural event in time. Only the Turkey Point events, which are both from one initiating event, were total losses of all AC power to a plant/site from grid-related causes during the time period 1980 through 1996. Although investigation of the specific reasons for the low number of grid events was outside the scope of this study, it may be inferred from a comparison of the frequency between the present study and NUREG-1032 results that grid failure is less likely to occur now than it was prior to 1985. Based on this experience, grid instability has not been an important contributor to LOSP frequency.

There were two electrical grid disturbances throughout the western states on July 2, 1996 and August 10, 1996 that received national media attention. Because of this, a specific search through the LOSP database for loss of power events on these dates was conducted. Only one event involving loss of electrical power was reported for either of these days and it was only a partial loss of power to Diablo Canyon 1 on August 10, 1996. This event does not meet the criteria established for the LOSP study, and thus was not included in the data analysis. If a plant experienced these grid disturbances on either of these dates, the effect on the plant electrical systems was insufficient to require the licensee to submit an LER. Due to the lack of reports on these dates, it is concluded that no plants experienced an LOSP due to those grid disturbances.

4.1.3 Severe-Weather Events

A plant is more vulnerable to severe-weather LOSP events while at shutdown, because although storms occur regardless of plant status, the conditional probability of losing power, given a storm, is higher for plants in shutdown conditions, as discussed in Section 3. Because of the increased number of plant activities that result in off-normal or single train configurations during shutdowns, a plant has a higher likelihood of experiencing a more serious result (i.e. LOSP event) than if the plant were in a normal configuration with all redundant equipment available. Thus, given the occurrence of a storm, it is more likely that offsite power will be lost during a shutdown storm than during a storm while the plant is operating.

Sixteen of the 22 plant events resulting from severe weather occurred at only 5 sites. These are Pilgrim, Crystal River, Brunswick, Millstone, and Turkey Point. The plants at these sites have diverse designs with little similarity in electrical power supply design or redundancy. Because all five of these sites are located on the east coast, it seems clear that their proximity to the ocean and its storms is a major factor in loss of power frequency. Of these five plant sites, Brunswick is the only site that is not in the top five for total number of LOSP events of all types. There is no indication of why other plant sites located on ocean shorelines have no losses of offsite power events. Investigation into the details of plant designs and their effects on weather vulnerability was outside the scope of this study.

4.2 Events by Cause

4.2.1 Proximate Cause

An alternative classification scheme was examined that segregates events according to the cause categories used in the data classification (e.g., equipment failure, human error, extreme environment condition). The plant centered power operation data indicate that approximately 60% of the events are caused by equipment failures, and approximately 26% of the events are caused by human errors. Conversely, the plant centered shutdown data indicate that approximately 32% of the events are caused by equipment failures, and approximately 59% of the events are caused by human errors. This is a reasonable result. Due to the increased number of maintenance and testing activities occurring during a plant shutdown, and due to an increased number of people working at the plant during any given hour over what is the normal staff level at power operation, the exposure to human error is increased substantially during shutdown conditions.

The frequency of each cause (number of events per year) is presented in Table 4.1, for plant-centered events. The point estimates and confidence intervals are displayed graphically in Figure 4.1. As can be seen, the frequency of every cause of LOSP goes up during shutdown, and the change is most dramatic for the human error events.

Table 4.1. Frequencies of causes of plant-centered events, excluding 'other' causes.

Cause, Status	**Events/ Years**[a]	**Maximum likelihood estimate and 90% confidence interval**[b]
external environment, Operation[c]	6/1188.6	2.20E-3, 5.05E-3, 9.96E-3
external environment, Shutdown	7/455.7	7.21E-3, 1.54E-2, 2.89E-2
Equipment, Operation	30/1188.6	1.82E-2, 2.52E-2, 3.42E-2
Equipment, Shutdown	26/455.7	4.00E-2, 5.71E-2, 7.92E-2
human error, Operation	13/1188.6	6.47E-3, 1.09E-2, 1.74E-2
human error, Shutdown	47/455.7	7.97E-2, 1.03E-1, 1.32E-1

a. Operating years for events during operation, outage years for events during shutdown.

b. The left and right numbers are the lower and upper ends of the confidence interval, and the middle number is the maximum likelihood estimate (MLE).

c. Only the initiating events were included for the operation estimates.

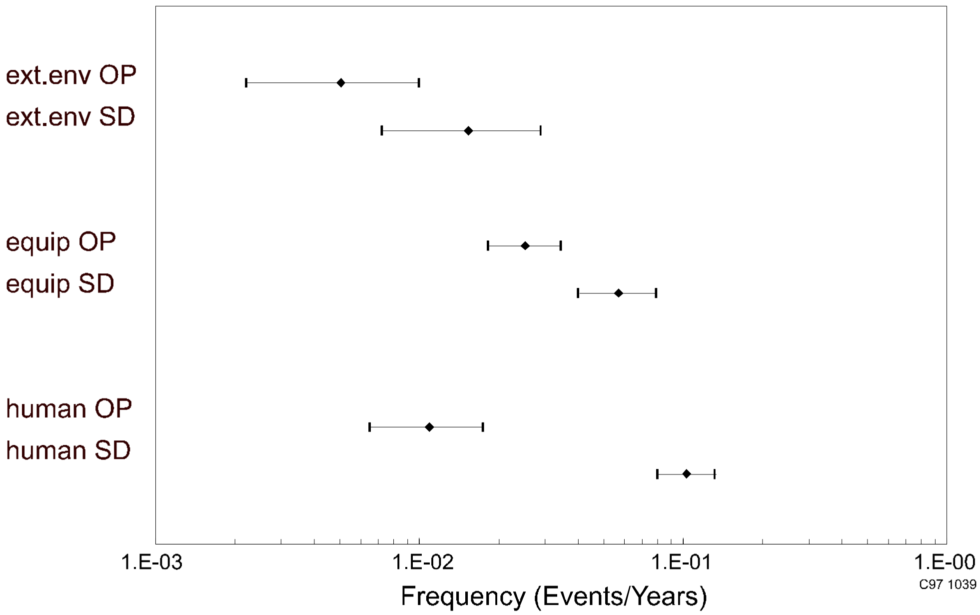

Figure 4.1. Frequencies of causes of plant-centered events.

4.2.1 Electrical Configuration

In order to determine the relative contribution to loss of offsite power due to electrical plant configuration, each event was reviewed to identify non-standard electrical system configurations that may have increased the vulnerability to a loss of offsite power or may have increased the recovery time. For most events, subjective analysis suggests that the total loss of offsite power might not have occurred had the plant electrical system been aligned in a normal configuration. In addition, for some events, recovery was delayed by complications resulting from a non-standard configuration. The results of this review are:

	# Events	# Non Standard	Fraction
Total	157*	54	.34
Shutdown	94	45	.48
Trip	63	9	.14

* The ‘Power Op’ events (loss of power events that did not result in a reactor trip), trips that caused LOSP events, and pre-full power license events were excluded from these counts.

Clearly the number of unit LOSP events is greatest when the unit is shutdown and in a non-standard electrical system configuration. This is consistent with expectations because Technical Specifications limit plant electrical configurations at power, and maintenance involving non-standard electrical system supplies is necessarily performed while shutdown. It was not in the scope of this study to determine the amount of time, as a percentage of both operating and shutdown periods, that a plant might be in a non-standard electrical configuration. Such information might allow for more detailed analysis to determine the risk of specific activities or configurations.

4.3 Recovery Times

The recovery time results presented in section 3 of this report are predictable, in that the recovery times are longer for the severe weather events compared to both the plant-centered and grid events. Due to the type of events that have caused the severe weather LOSP events, (hurricanes with widespread damage, and other storms that affect large geographical areas), it is reasonable to expect that restoration of equipment would be a lengthy process.

The time trend that indicates increasing recovery times (Figure 3.7), even while LOSP frequencies are decreasing (as shown in Table 3.8) is not surprising. Several factors combine that may explain the increase as a real trend:

- Through the 1980s and 1990s, plant operators became more deliberate due to higher standards of operator performance and increased caution of licensee management, and plant procedures were enhanced with greater detail, such that recovery from an abnormal event would be expected to take more time now than it did in the 1970s. What may have been estimated to take 15 minutes in earlier years of nuclear power operations may take closer to 45 minutes now.
- The data in the NSAC report[3] may err on the optimistic side. Several entries discuss the availability of a cross-tie option to the other unit on the same site, while the LERs reporting the same events do not mention either an attempt to use the cross-tie to restore power or even the existence of the option to cross-tie.
- The option to use a cross-tie to a sister plant is rarely considered now, except in extreme circumstances. There is greater concern now than before about a cascading effect on another plant.
- Review of the plant centered events with recovery times greater than 200 minutes, all occurring after 1986, revealed that the majority of them (14 of 17) involve severe equipment failure. Licensees have become extremely conservative with respect to event recovery. Root cause investigation now takes priority over immediate repair activities, provided there is an emergency power source (EDG) supplying power to the safety equipment. While no engineering evaluation was performed to determine if the rate of equipment failure is increasing, the discussion of the first bullet above explains the longer time to restore power following an equipment failure.

Additionally, it is reasonable that plants designed with fewer alternate power sources (NUREG-1032 design group I3) also tend to have longer recovery times (section 3.4.5). The design features of I3 plants are either no fast transfer to another offsite power source or no independence in the fast transfer sources, in combination with limited or no independence of the incoming power lines. The I1 plants are designed to automatically transfer to another offsite power source, and if that source fails there is yet another transfer to another offsite power source. For details of these groupings and design features, refer to NUREG-1032, Tables A.2 and A.3. As displayed in section 3.4.5, the plants categorized as I3 in NUREG-1032 have statistically larger recovery times than the I1 category plants, a result similar to NUREG-1032 results. This, again, is not unexpected, simply due to the definition of the group characteristics, and the application of the definition to the plants being considered in the analysis. If a plant has two alternate sources of offsite power, it is reasonable to assume that recovery from any type of power loss event would be quicker than if the plant has either no alternate source of offsite power or has all power lines coming through the same path into the switchyard.

4.4 Station Blackouts

In NUREG-1032, a station blackout (SBO) is defined as the complete loss of alternating current (AC) electrical power to the essential and nonessential buses in a nuclear power plant. Several incidents at nuclear power plants have occurred that could be classified as precursors to station blackout. This study found 16 LOSP events in which a LOSP and loss of emergency AC power occurred simultaneously. However, none of these events had the characteristics of a SBO as modeled in NUREG-1032 and most PRAs. That is, the duration of the event and the need for accident mitigation systems powered from emergency AC power were not present in the events.

Two of the 16 events occurred during power operation. The other 14 events occurred when the plants were shutdown or during refueling, when station blackout regulatory requirements are reduced and the limiting condition for operation (LCO) requirements, in terms of numbers of offsite and emergency AC power supplies available, are also reduced. All events required manual operator actions to restore power. Most losses were caused by human errors while conducting tests or maintenance activities. Each loss had minimal impact on decay heat removal.

The two power-operation events lasted one minute and 11 minutes respectively. U. S. NRC Regulatory Guide 1.155[8] specifies that the minimum coping time for nuclear power plants during a station blackout is at least 2 hours, which is much greater than the durations of these two events. Using average values for the LOSP frequency (0.04/plant critical year for plant-centered events), EDG failure to start probability (0.01) and a common cause alpha factor (0.03) for two EDGs failing to start, the partial sequence frequency for loss of offsite power and two emergency diesel generators failing to start equals 1.6×10^{-5} [$= 0.04\ ((0.01)^2 + (0.03)(0.01))$] per plant critical year. Failure to recover offsite power or the EDGs and additional system failures would be necessary for core damage to occur. Consideration of recovery would reduce this number by about an order of magnitude. Therefore, these events do not exhibit frequency or severity characteristics that are compatible with the SBO events modeled in NUREG-1032.

Six of the 14 shutdown events occurred while the reactor was defueled, and five events during refueling outages. The plant configurations when these events occurred would not exist during power operations and are therefore not representative of the expected frequency or severity of SBO events at power operations. The length of time when electrical power was lost from the safety buses ranged from 40 seconds to 67 minutes. The only increase in temperature occurred during one event in which the temperature in the spent fuel pool increased about 3 degrees. The consequences of these events on core and spent fuel cooling were minimal.

5. CONCLUSIONS

This section highlights the major technical findings of the study.

- Not all LOSP events at power cause a reactor trip, because the designs of some plants allow the plants to operate while using emergency power. Following the precedent of NUREG-1032, this report provides estimates of the frequency of LOSP initiating events at power, i.e., LOSP events that caused a reactor trip. This report also provides the frequency of LOSP events during shutdown, ignoring whether such an event would have caused a trip at power.

This set of conclusions concerns LOSP event frequency:

- NUREG-1032 found that plant-centered events accounted for the majority of the losses of offsite power. This study supports that finding, with plant-centered events clearly dominating LOSP frequency during power operation, as well as during non-power modes of operation. Events induced by severe weather are much less frequent, and grid-related events are still less frequent.

- LOSP frequency for plant-centered events is significantly higher during shutdown modes of operation than during power operation, by a factor of about four. While at power, the expected frequency for plant-centered LOSP initiating events is on the order of 1 event in 24 reactor critical years. When not at power, the plant-centered frequency of LOSP events is 1 event in about 6 reactor shutdown years. This result would be true even if non-initiating events at power were combined with the initiating events. For severe-weather events, the estimated frequency is also higher during shutdown than during power operation, by a factor of three. For grid-related events, too few events occurred to allow any conclusion.

- For plant-centered initiating events at power, no statistically significant plant-to-plant variability in LOSP frequency was found. A decreasing trend in time was not quite statistically significant, and therefore was not modeled. Unexplained variance was seen between years, and this variance was used to obtain an interval estimate for the frequency, wider than a simple confidence interval.

- For plant-centered events during shutdown, significant statistical variability was found among the plants, but no time trend was seen. Therefore, a population variability distribution was developed, as discussed in Section 3. Data at individual plants were used to update this overall distribution. Plant-specific results are presented in Appendix B.

- The majority of plant-centered LOSP events at power are caused by equipment faults, with a smaller portion being induced by human error. During shutdown modes, the opposite holds, with human errors being the major contributor.

- Plant-centered initiating events have become less frequent since the time period studied by NUREG-1032. A clear downward trend can be seen in the frequency from 1969 through

1996. No effect was found in the data that could be related directly to the Station Blackout Rule (10 CFR 50.63), which was published in June 1988.

- The LOSP frequency from grid-related events in the period covered by this study was very small. During this period, there were only six events that could be classified as grid-related, and one of these involved only a momentary loss (grid instability). This is less frequent than found in NUREG-1032 by a factor of about 10. In addition, no grid-related events occurred in the 1990s, in spite of the occurrence of several widespread losses of power to the public.

- During the time period of this study, there was only one complete LOSP event due to a grid disturbance. A fire near Turkey Point caused a grid failure that resulted in both units experiencing a LOSP event.

- The frequency of LOSP events due to severe weather exhibited statistically significant site-to-site variability for both power and non-power operating modes. This is to be expected, as some plants, merely because of their geographic location, will tend to have increased exposure to severe weather. For this report, plant-specific estimates were obtained, to the extent possible, from the small number of recorded events.

- Analysis of station blackout risk was outside the scope of this study. However, 16 station blackout events were identified during the data review in which a power plant had no AC electrical power from any source for up to one hour. Only two of these events occurred during power operations, and the longest of these two events lasted 11 minutes, which is well below the minimum coping time specified in U.S. NRC Regulatory Guide 1.155.[8] None of these 16 events had the characteristics of a SBO as modeled in NUREG 1032 and most PRAs. That is, the duration of each event was small and the need for accident mitigation system powered from emergency AC power was not present in the events.

The next set of conclusions concerns LOSP event recovery times:

- For plant-centered events caused by human error, recovery times during shutdown are slightly shorter than at power, and the difference is barely statistically significant. For other types of events, and for the plant-centered events overall, no statistically significant difference could be seen between recovery times during shutdown and during power operation. Therefore, the distinction between shutdown and operation was ignored in the analyses of recovery times.

- As found by NUREG-1032, the severe-weather events have significantly longer recovery times than the plant-centered events. Too few grid-related events occurred during the period of this study to permit any summary statement about their recovery times.

- The recovery time of plant-centered LOSP events appears to be longer than was found in NUREG-1032, and an increasing trend is seen in the 1980-1996 recovery times.

- NUREG-1032 defined plant design classes I1, I2, and I3, which were believed to have increasing recovery times. For plant-centered events in the current study, the 1980-1996 recovery times were ordered as predicted by NUREG-1032, and the pattern was almost statistically significant. This ordering, however was only seen in the shutdown events; an analysis of only the initiating events did not result in this ordering.

6. REFERENCES

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6. Accident Sequence Precursor (ASP) Database, maintained by the INEEL for the NRC.

7. Poloski, J., et al., “Rates of Initiating and Follow-On Events at U.S. Commercial Nuclear Power Plants, 1987 through 1995,” Draft, April, 1998.

8. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.155, “Station Blackout,” August 1988.

GLOSSARY

1032 category - The category taken from NUREG 1032 to which the event was assigned. The three categories are plant-centered, grid-related, and severe-weather.

Cause - The direct cause of the electrical transient resulting in the loss of offsite power.

Docket - Three digit docket number of the affected unit.

Grid - Interconnected grid transmission lines , outside direct plant control .

Grid-related - Events involving failure of the offsite power grid. If such events are caused by weather or storm, they are classified as severe-weather events, not as grid-related events, even though the grid was involved.

Loss of offsite power - Simultaneous loss of electrical power to all unit safety buses, requiring the emergency power generators to start and supply power to the safety buses.

LOSP initiating event - A loss of offsite power that occurs during power operation and causes the reactor to trip. At some plants an LOSP event at power is not necessarily an initiating event.

Plant-centered - Following the approach of NUREG-1032, plant-centered events are those in which the design and operational characteristics of the plant itself play the major role in the cause and recovery time of the loss of offsite power. Plant-centered failures typically involve hardware failures, design deficiencies, human errors, and localized weather-induced faults (e.g., lightning).

P-value - The probability that the data set would be as extreme as this, if the assumed model is correct. It is the significance level at which the assumed model would barely be rejected by a statistical test. A small p-value indicates strong evidence against the assumed model.

Recovery time - The time (in minutes) at which power becomes available from non-emergency sources to power the loads on the plant emergency AC buses. Note that this may be different from the time at which the failed source was recovered, or the time at which power was actually restored. Put another way, time to recovery is the time to which power from a non-emergency source would be available if the emergency AC generators were not available to provide power. Unless the event report states otherwise, it is assumed that a minimum of 1 minute is required for operators to restore offsite power.

Severe weather - Weather with forceful and non-localized effects. A loss of offsite power is classified as a severe-weather event if it was judged that the weather was widespread, not just centered on the plant, and capable of major disruption. An example is storm damage to transmission lines instead of just debris blown into a transformer. This does not mean that the event had to actually result in widespread damage, as long as the potential was there. For example, a tornado might affect one plant unit and jump past the other; because of its potential, it would still be counted as a severe-weather event. Lightning strikes, though forceful, are normally localized to one plant, and so are coded as plant-centered.

Statistically significant - having a p-value of 0.05 or smaller. For example, if a trend is statistically significant, the model with no trend would be rejected at a significance level of 0.05 or larger.

APPENDIX A

METHODS OF DATA ANALYSIS

This appendix describes the methods for the basic data characterization and the estimation of occurrence frequencies. The descriptions give details of the methods and discussion of some of the reasoning behind the choice of methods. Results of these methods applied to the current set of data are presented in Appendix B.

A-1. PRELIMINARY ANALYSIS

A-1.1 Quality Checks on Event Coding

Frances, revise.

The Quality Assurance (QA) verification that was performed consisted of comparing the events collected for this LOSP study (including all the events that did not meet the rigorous definition of a LOSP event for this report) to other published studies that evaluated events involving losses of offsite power to the plants. These studies are listed as References 1-7 of the main report (not the Appendix A references) and are summarized here:

- NUREG-1032
- EDG Power System Reliability Study report
- NSAC182/203
- AEOD Grid Performance Factors report
- Evaluation of Loss of Offsite Power due to Plant Centered Events, AEOD, March 1993
- ASP database
- Initiating Events Study report

The purpose of the comparison was to ensure that all appropriate events were included in the LOSP event analysis. During this comparison, two events were determined to belong in the LOSP study that were not already included in the database, primarily because during the initial screening the LER abstract did not contain enough information for the reviewer to identify the event as pertaining to a loss of site power.

Additionally, the data coding performed for this study was compared to the data coding performed for the Initiating Events study to examine the comparability of the two studies. Some differences in event coding were found, due primarily to the difference between the objectives and methodologies of the two studies. The Idaho National Engineering and Environmental Laboratory (INEEL) staff performed a comparison between the external plant events coded by the INEEL subcontractor and the internal plant events coded by INEEL staff to ensure that events were not included in the database twice. Finally, a second engineer reviewed all events to verify the recovery times. During these reviews, some of the event data were modified in the database.

The plant-centered trip events through 1985 were compared to those in NUREG-1032. Fifteen of these events had recovery times in both reports, and five NUREG-1032 times differed from the initial findings in this study. After detailed review of the event reports and consideration of when power could have been restored, four recovery times were reduced for use in this study. Due to the analysis results that indicated an increasing trend in recovery times (Figure 3.7), the longest recovery time events were reviewed in detail. Of all the events considered in this study, approximately 52 events received a detailed second review, and 12 of these events had some data modifications after a detailed evaluation.

A-1.2 Events Used for Analysis

For the years 1980 through 1996, 176 events were found in which a loss of offsite power to all safety buses and a resulting demand for emergency power occurred. Only events that caused a total loss of offsite power to all safety buses were considered.

Only events that occurred after the full power license date (and before decommissioning) were considered in the analysis, to eliminate influencing the results by the learning curve that may occur between the low power license date and the full power license date. This eliminated three events, and all consideration of the Shoreham plant events.

Of the remaining 173 events, a distinction was made between LOSP events and LOSP *initiating* events. Initiating events are defined for this study as the LOSP events that cause a reactor trip. In eleven events occurring at power, the reactor did not trip, because of the design of that particular plant. Although a similar event would presumably have caused a trip at some plants, these events were not considered as initiating events. In an additional five events, a plant trip caused the LOSP rather than the LOSP being the initiator. These events were also not counted as initiating events. Thus, only 157 events were used for the analysis of event frequencies, 63 initiating events at power, and 94 events during shutdown. Note that all LOSP events during shutdown were counted, even at plants where a similar event might not have caused a trip during power operation.

For the analysis of recovery times, all 173 events were considered relevant, in principle. When the recovery time for an event was reported or could be estimated, that time was used. However, groups of events were pooled or analyzed separately based on whether their recovery times appeared similar or not.

A-1.3 Critical Hours and Shutdown Hours

The critical hours for each plant were taken from the INEEL database CRITHRS (INEEL, 1997). These hours are drawn directly from the plant monthly operating reports, submitted by the licensees to the NRC. This database gives critical hours by month, beginning in January 1984. The only recognized inaccuracy in using this database for the present report concerns the month when a plant obtained its full power license, because information was unavailable on how many of the critical hours for the month occurred after the full power license. This inaccuracy is negligible. The shutdown hours for each year were obtained by subtracting the critical hours from the calendar hours in the year (8760 hours except in a leap year, or less if the plant received its full power license during the year or was decommissioned during the year.)

For the years 1981 - 1984, the UDI database (Utility Data Institute, 1997) was used. This gives dates of all outages, and their durations in hours. To use this data, a few reported overlapping outages were consolidated, and the plant names “Connecticut Yankee” and “Genoa Two” were interpreted as “Haddam Neck” and “La Crosse,” respectively. This database goes back to 1981, and lists outages that began in 1980 only if they extended into 1981. The TMI 1 outage, which began before 1980, was not listed but was inserted manually. From this information, the shutdown hours for each plant and each year from 1981 through 1983 were obtained. The critical hours were obtained by subtracting the shutdown hours from the calendar hours for each plant and year.

For 1980, the critical hours and shutdown hours were not obtained. As discussed in section B-2 of Appendix B, 33% of the 1980 calendar hours were estimated to be shutdown hours.

Most of the frequencies presented in this report are expressed in terms of years. For this purpose, a calendar year was defined as 365 days, that is, 8760 hours. A critical year was defined as 8760 critical hours for a reactor, and a shutdown year was defined as 8760 shutdown hours for a reactor. The time period from 1980 through 1996 had 17.014 calendar years, because of the five leap years in that period. This approach seemed the simplest way to convert results in terms of hours to results in terms of years.

The critical times and shutdown times are summarized in Tables C-4 and C-5 of Appendix C.

A-1.4 Defining Appropriate Subsets of the Data

One major goal of the analysis is to produce estimates of event frequencies and recovery times, for use in PRA studies. For this, the data must be divided into qualitatively similar subsets. Four ways of dividing the data into subsets were considered, and used where appropriate:

1. A PRA usually considers the operating state of the plant being considered — the plant is assumed to be operating at power, or, occasionally, it is assumed to be in a shutdown condition. Therefore, the data should be examined to see if the desired quantities, that is, the event frequencies and times to recovery, differ for *operating* plants and *shutdown* plants.

2. NUREG 1032 (Baranowsky, 1988) classified LOSP events as *plant-centered*, *grid-related*, and caused by *severe weather*. Two reasons for this classification were that the classes involved different mechanisms, and that they seemed to have different recovery times on average. Therefore, these divisions were considered for the present study as well.

3. The events were classified according to their causes: *equipment problem*, *human error*, *external environment*, and *other*. Severe-weather events were, by definition, all caused by the external environment, but plant-centered and grid-related events

could have a variety of causes. Therefore, the data were analyzed to see if the subsets of plant-centered and grid-related events deserved separate treatment. In the end these distinctions were not used, but they were considered.

4. About 15% of the events lasted only a very short time, about one minute. For many of these, it was judged that power could have been recovered in about one minute. Therefore, events for which power was recovered, or could have been recovered, in less than two minutes were called *momentary*. The others were called *non-momentary*. The recovery times could typically be characterized by a lognormal distribution for the non-momentary events plus a spike at one minute for the momentary events. The easiest way to present the results was to analyze the momentary and non-momentary events separately.

The above conditions can be considered simultaneously, for example, plant-centered non-momentary events caused by human error during shutdown. The analysis of frequencies was not required to use the same data groupings as the analysis of recovery times. For example, for frequencies the plant-centered non-momentary events were divided into two classes, initiating events and shutdown events, because the frequencies were clearly different. For recovery times, on the other hand, all plant-centered non-momentary events were considered as one class of events, because the recovery times did not seem to be related strongly to the shutdown/operation distinction.

A-1.5 Statistical Tools for Comparing Data Subsets

The data were evaluated to determine the most appropriate partitioning for subsequent analysis. For example, plant-centered events during shutdown could be divided into three subsets according to their causes: equipment problems, human error, or external environment. Both graphical methods and formal statistical tests were used to see whether the subsets of the data were similar enough that they could be combined. The methods are described in many statistical texts, and in the references cited below. The specific tools used are presented here, for comparing recovery times and for comparing event frequencies.

A statistical test can be used to show *statistical* significance, that is, to show whether the data give strong evidence of a difference between the subsets. A graphical comparison can be used to show *engineering* significance, that is, whether the differences among the subsets are large enough to be important in practice. Both kinds of significance were considered for the presentations of this report.

A-1.5.1 Frequencies

A frequency is a rate of occurrence, with units 1/time. If the events are independent and generated by a Poisson process with constant occurrence rate, standard analysis tools are available. Engelhardt (1994) explains these tools, which are briefly summarized here.

For a graphical comparison, the maximum likelihood estimate (MLE) and a confidence interval for the frequency, λ, were calculated for each subset. These intervals were plotted side by side to see if they overlapped.

The Pearson chi-squared test was used to test equality of the frequencies. The significance level, or p-value, was calculated using a large-sample approximation. A p-value of 0.05 is typically calculated with adequate accuracy if the number of events is at least as large as the number of subsets being compared. Engelhardt summarizes further refinements on this rough guideline.

A-1.5.2 Recovery Times

A box plot (also called a box-and-whisker plot) was constructed for the recovery times of events from each subset, and the boxes were compared to see how much they overlapped. Box plots are constructed as follows in the implementation by SAS/INSIGHT (1995). The lower quartile of a distribution is the 25th percentile, the upper quartile is the 75th percentile, and the interquartile range is defined as the distance from the lower to the upper quartile. For a distribution defined by data, one fourth of the data values lie at or below the lower quartile, and one fourth of the values lie at or above the upper quartile. The median is the 50th percentile, with half of the data values lying on each side of the median. A box plot shows a box going from the lower quartile to the upper quartile, with a line at the median. The whiskers are two lines extending out from the ends of the box. Each whisker has length up to 1.5 times the interquartile range; however if this length makes the whisker extend beyond the most extreme data value, the whisker stops at the most extreme data value. Any points beyond the whiskers are shown individually. Appendix B contains box plots, Figures B-9 through B-12 and B-22 through B-24. Because recovery times (times to recovery of offsite power) have highly skewed distributions, the box plots were calculated using $\log_{10}$(recovery time).

Box plots provide an informal graphical comparison of distributions. More formal comparisons were carried out by the statistical tests of equality of distributions, in particular the Wilcoxon and Kolmogorov-Smirnov tests for two distributions, and the Kruskal-Wallis test for two or more distributions. These tests were used to supplement the qualitative evidence of the box plots. The tests are implemented by the SAS (1990) procedure NPAR1WAY.

A-1.5.3 Non-Independence of Events and Recovery Times

The statistical techniques given above all assume that the quantities measured — event counts or event recovery times — are statistically independent. However, the event counts and recovery times are not always independent, as illustrated by the following examples. An equipment problem caused LOSP at units 2 and 3 of Peach Bottom, and the times to recovery (event recovery times) were identical (LER 27788020). A fire caused a collapse of the grid in south Florida; units 3 and 4 of Turkey Point both lost offsite power, and the recovery times were similar (LER 25185011). A hurricane caused loss of power at Millstone 1 and Millstone 2, with recovery times of similar magnitude (LER 24585018). In the cases just mentioned, the event occurrences were positively correlated, that is, the probability of LOSP at the second unit increased when the first unit lost power. The recovery times were also positively correlated, that is, the two recovery times tended to be similar in length. A possible negative correlation is seen when Rancho Seco experienced two grid instabilities within two months of each other (LERs 31281034 and 31281039). The second event had a shorter recovery time than the first event, possibly because of the experience acquired during the first event.

These examples illustrate that a few dependencies exist, for plant-centered events, grid-related events, and severe-weather events. The statistical analyses dealt with these dependencies as follows.

Frequencies. Event frequencies per site year are not calculated here. Instead, the analysis presents frequencies per plant critical year or per plant shutdown year, for three reasons. First, most plant-centered events did not involve multiple units. Therefore, an analysis of frequencies by plant is natural, for plant-centered events. Second, even for severe-weather events, which typically affect all the units at a site, the frequencies were analyzed by plant rather than by site, for the following reason. The frequency of non-momentary events during shutdown was somewhat larger than the frequency during operation. (The statistical significance was borderline.) Therefore, the frequency of shutdown events was estimated per shutdown hour, and the frequency of LOSP initiating events was estimated per critical hour. For a single reactor, shutdown hours and critical hours are easily defined. For a site, however, critical hours and shutdown hours are not easily defined. If one unit is shutdown and one is operating for a full year, does the site experience both a shutdown year and a critical year? Because of this conceptual difficulty, no attempt was made to define site critical time and site shutdown time. Finally, even if it were clear how to define a site shutdown year or a site critical year, it might have been difficult to obtain the numbers, for sites where both units had numerous short outages. For all these reasons, event frequencies were analyzed by plant, not by site.

The above discussion avoided the severe-weather momentary events, which were too rare to show a significant difference between initiating events and shutdown events. The above approach was followed for them, but only for consistency of presentation.

The plant-centered initiating events were treated as independent, and the plant-centered shutdown events were treated as independent. This had the following effects when the standard statistical formulas were applied. For plant-centered LOSP events, dependencies were rare; there were only seven pairs of events out of 130 plant events, with two of those pairs involving one operating unit and one shutdown unit. Therefore, the effect of ignoring the dependencies is small. The five grid-centered events considered for frequencies included two dependent pairs. Because of the dependencies, and because the number of events was so small, no statistical analysis was performed. The severe-weather initiating events had five dependent pairs out of 22 plant events, a substantial portion. Indeed, every severe-weather event at a multiple-unit site affected all the units. Because between-plant differences were seen, the empirical Bayes method was used to find plant-specific frequencies. The empirical Bayes prior distribution was estimated from event counts by plant unit rather than by site, giving sites with multiple units an extra influence on the estimated prior distribution. This influence apparently has no systematic effect on the estimated prior distribution. Other effects of the dependencies are not known, but explicitly modeling the dependencies seemed unjustified for so few events. Plants that had experienced site-wide LOSP events had similar plant-specific estimated frequencies, as would be expected.

Recovery Time. Momentary events have a recovery time of about one minute, by definition. The data for non-momentary events were analyzed for components of variance, as follows. In the end, it was decided that the between-unit and between-site variation was not worth modeling. However, consideration of the components of variance justified the final simple analysis method.

Missing values were ignored. The distribution of log(recovery time) is more nearly symmetrical than the distribution of the recovery time itself. Because the methodology uses variances of the distributions, and because variances are better descriptors of symmetrical distributions than of highly asymmetrical distributions, the analysis was performed on log(recovery time). Natural logarithms were used.

The following model was assumed:

$$\text{log(recovery time)} = \mu + X_{\text{site}} + X_{\text{event}} + X_{\text{resid}} \tag{A-1}$$

where the *X*s are independent random variables. That is, the log(recovery time) of a random event at a random plant unit has an overall average value μ, plus a term that depends on the site, plus a term that depends on the particular event (the human error, equipment problem, hurricane, etc.), plus a residual random term. The residual variation is indistinguishable from variation between units, because the only way to observe different recovery times from a single event is to observe the recovery times at different units; the event itself cannot be repeated to observe its effect during the next trial. Because a single event occurs only at one site, and can affect both units at a site, event is nested within site and residual variation is nested within event. In the data analysis, event date was used as a surrogate for event.

For a recovery time from a random event at a random site and random plant unit, the mean is the sum of the means and the variance is the sum of the variances. One way of modeling the *X* terms is to assign them all mean zero, so that the overall mean is μ. The variance is

$$\sigma^2_{\text{total}} = \sigma^2_{\text{site}} + \sigma^2_{\text{event}} + \sigma^2_{\text{resid}} \ , \tag{A-2}$$

where each σ^2 is the variance of the corresponding *X*. This equality does not require normal distributions; it is a property of variances of independent random variables.

The value σ^2_{site}, σ^2_{event}, and σ^2_{resid} are called the *components of variance*. They are estimated from the data, using the SAS procedure VARCOMP (SAS 1990), with the REML (restricted maximum likelihood) estimator. REML estimation, explained by Searle et al. (1992), has become one of the most accepted methods for estimating variance components with unbalanced data. If the data contain one or more events that affect multiple units, σ^2_{resid} can be estimated. If the data contain one or more events at a single site, σ^2_{event} can be estimated. And if the data contain events from more than one site, σ^2_{site} can be estimated.

In every case analyzed, σ^2_{resid} was estimated to be a very small fraction of σ^2_{total} in Equation (A-2), at most a few percent. Therefore, it was ignored, as follows. For each event affecting multiple units, the recovery times were averaged, and this single recovery time was assigned to the site event. The distribution of recovery times was estimated using this averaged data, one recovery time for each site event. This eliminates the major dependence among the recovery times.

In addition, σ^2_{site} was always smaller than σ^2_{event} . When it was much smaller, a few percent, it was dropped from the model. When σ^2_{site} was only somewhat smaller, less than half as large as σ^2_{event}, engineering understanding was used to decide whether to drop σ^2_{site} from the model.

A-2. QUANTIFYING THE EVENT FREQUENCIES

The preceding section considered which groups of events should be analyzed together. This section of the report presents the methods used in the estimation of frequencies. Section A-3 below presents the methods used in estimation of the distribution of recovery times.

The statistical method chosen for analyzing a subset of the data depended on the complexity of the data set. A data set with only a few event occurrences must be analyzed simply. A data set with a large number of events requires more complicated modeling, so that the estimates can reflect the trends or patterns that are evident in the data. The three models used are described here, beginning with the simplest.

The assumption underlying all the models is that the events occur following a Poisson process, so that in any small time interval Δt, the probability of an event occurring is $\lambda\Delta t$. The basic properties of this model are described by Engelhardt (1994) and in many statistics books. The different models are determined by the form of λ, specifically, whether λ is constant, or dependent on the specific plant, or dependent on the calendar year. No data set was large enough to show dependence on both.

In every case, a desired result is a Bayesian distribution for the event occurrence frequency or frequencies, that can be used in PRAs. In some models, a Bayesian distribution is obtained directly, by using the data to update a prior distribution. The prior distribution either is chosen to be noninformative (not reflecting any strong prior information or belief), or is inferred from the data. In other models, classical (non-Bayesian) methods are used, and a Bayesian distribution is constructed afterwards so that the Bayesian uncertainty intervals match the classical confidence intervals. The result is a Bayesian distribution that depends on the data but not on prior information or belief.

After the models are described, a separate section explains the data-analysis methods used to decide which model is most appropriate.

A-2.1 Constant Generic Frequency

Here λ is assumed to be the same for all plants and all time. This simple model is appropriate when very few events have occurred. Let n be the observed number of events in t critical hours. The Jeffreys noninformative prior distribution is updated by the data to produce a posterior distribution, which has a gamma form. The two parameters are the shape parameter, equal to $n + ½$, and the scale parameter, equal to t hours. The mean of the distribution is $(n + ½)/t$. For further explanation, see Engelhardt (1994).

A-2.2 Constant Frequencies, Differing Among Plants

This model says that the ith plant has an event frequency λ_i, which is constant over time but possibly different from the frequencies of the other plants. The other main assumption is that the events occur independently, at a plant and among various plants. The model used was a parametric empirical Bayes model. The plants were modeled as belonging to a family. Any one plant was treated as being drawn randomly from the family. The distribution of λ_i within this family was modeled parametrically, and for mathematical convenience, the distribution was assumed to be a gamma(a, b) distribution. (During any data analysis, this assumption was checked to make sure that it was consistent with the data.) Therefore, the model was that λ_i for the ith plant is generated randomly from a gamma(a, b) distribution, and that the random number of failures in the observed t_i hours (operating or shutdown hours, as appropriate) is Poisson with mean $\lambda_i t_i$.

The empirical Bayes method estimates a and b from the data. That is, the likelihood function for the data is based on the observed number of event occurrences and (operating or shutdown) hours at each plant and the assumed gamma-Poisson model. This function of a and b was maximized through an iterative search of the parameter space, using a SAS routine given by Engelhardt (1994). In order to avoid fitting a degenerate, spike-like distribution whose variance is less than the variance of the observed failure counts, the parameter space in this search was restricted to cases where b was less than the total number of observed critical hours. The a and b corresponding to the maximum likelihood were taken as estimates of the gamma distribution parameters representing the observed data for the failure mode.

The resulting distribution was then updated by the data for each plant, to produce a plant-specific distribution for λ_i. A refinement, due to Kass and Steffey (1989) was also used, which adjusted these plant-specific distributions to account for the fact that a and b were only estimated, not known exactly. The form of each adjusted plant-specific distribution was approximated by a gamma distribution, which is printed in the report. For further discussion, see Engelhardt (1994).

A-2.3 Trend in Calendar Time, with No Differences Among Plants

If a trend in time was postulated, but no strong differences between plants were evident, the form of the occurrence frequency was modeled as $\lambda = \exp(a + by)$ or equivalently, $\log(\lambda) = a + by$, where y denotes the calendar year. If b is negative, the trend is decreasing. This model is a *loglinear* model, and methods for analyzing data from such a model are explained by Atwood (1995) and by certain advanced texts. The SAS procedure GENMOD (SAS 1993) was used to analyze data using this model. In nearly all the cases considered in this report, either the trend was not statistically significant or the model fit badly because of one or more outlying years. Only in one case did the trend model fit the data well and show a statistically significant trend: For comparison with NUREG-1032, the data for plant-centered initiating events were extended back to 1969, and a decreasing trend was seen. For plant-centered initiating events using the 1980-1996 data, the trend was significant, but substantial lack of fit existed.

To model a trend with lack of fit, we assumed that the count during any year was not Poisson distributed, but instead had a negative binomial distribution. The negative binomial distribution was chosen because it is commonly used when extra-Poisson variance must be modeled. The mean count was assumed to change exponentially over time, and the coefficient of variation was assumed to be constant. This led to a three-parameter model. The three parameters were estimated by maximum likelihood, and the asymptotic distribution of the maximum likelihood estimators was used to quantify the uncertainty in the estimates. Mathematically, this is identical to an empirical Bayes analysis with a trend in the mean; however, the interpretation is different.

The program to do this was written in SAS. The output of the program was compared to GENMOD output, both for some test data and for the plant-centered initiating event data, and the results were consistent: the three-parameter model showed a similar trend, but: (a) the three-parameter model saw less statistical significance in the trend than did GENMOD, (b) it calculated a wider confidence band around the fitted trend than did GENMOD, and (c) the increase in width of the confidence band was consistent with the size of the lack-of-fit statistic produced by GENMOD. These comparisons were just as expected.

A-3. ESTIMATING THE DISTRIBUTION OF RECOVERY TIMES

This section of the report presents the methods used in estimation of the distribution of recovery times. Recovery times less than 2 minutes were excluded from these analyses.

A-3.1 Independent Identically Distributed Recovery Times

As explained in the recovery time portion of section A-1.5.3, the recovery time data were analyzed for components of variance. In every case, we concluded that only one component of variance needed to be modeled, the component corresponding to events. The recovery times from different events were then treated as independent identically distributed random values.

To characterize the distribution of the recovery times, the gamma, lognormal, and Weibull distributions were considered. The parameters of the gamma and Weibull distributions were found by maximum likelihood estimation. The lognormal parameters were estimated by treating log(recovery time) as normally distributed, and calculating the usual unbiased estimators of the mean and variance.

The model that gave the largest value of the likelihood was regarded as the best-fitting model. In addition, the Shapiro-Wilk test of normality was performed. Royston (1988) describes this test as “one of the most powerful ‘omnibus’ procedures for testing univariate nonnormality.”

A-4. REFERENCES

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APPENDIX B

RESULTS OF DATA ANALYSES

This appendix describes the results of the data analyses, using the methods presented in Appendix A. The analyses of initiating event frequencies and of recovery times are driven by different considerations, and are completely separate. Initiating event frequencies are presented first, and recovery times second.

B-1. PRELIMINARY ANALYSIS OF INITIATING EVENT FREQUENCIES

For the reasons explained in section A-1.5.3 of Appendix A, frequencies were analyzed by plant, not by site. Critical time and shutdown time for each plant were obtained for 1981-1996. To make use of the 1980 events, the shutdown portion of 1980 was estimated as follows. Using Table C-4, the industry percentage of shutdown time was calculated for each year. From 1981 through 1987, the percentage was between 31% and 35%, with no evident trend in those years. The average was 33%. Therefore, the shutdown time *for each plant* in 1980 was estimated as 33% of the calendar time for the plant, and the critical time was estimated as the remaining time. More accurate information could be obtained only with difficulty, by careful examination of many monthly operating reports now stored on microfiche; this was not considered an effective use of resources. Trend analyses might be especially sensitive to the 1980 shutdown or critical time. Therefore, as a check, we reran each trend analysis setting the 1980 shutdown time to 31% and 35% of the 1980 calendar time, and saw little difference in the conclusions of the analysis. Only the results using 33% are presented here.

The momentary and non-momentary events were analyzed separately. Eight of the 24 momentary events occurred at one plant, Pilgrim. Therefore, Pilgrim was regarded as an outlier, with respect to momentary events. The analysis of momentary events below excludes Pilgrim.

To explore the frequency of initiating events, we considered those events in Tables C-1 through C-3 that had a ‘1’ in the column ‘Initiator.’ This excluded the shutdown events, the power-operation events, and the five trip events for which the trip preceded the LOSP. To explore the frequency of the shutdown events, we considered those events with S or S* in the ‘Status’ column. Assuming homogeneous data sets of independent events, point estimates and 90% confidence intervals were calculated for the frequencies (events per critical year or events per shutdown year.) The statistical method is explained in Appendix A. These estimates and intervals are shown in Figures B-1 and B-2. The identifiers on the left show whether the events are plant-centered (P), grid-related (G), or severe-weather (W), and whether the event was a reactor trip or a shutdown event. The identifiers also show the number of events divided by the relevant number of reactor years in the 1980-1996 period.

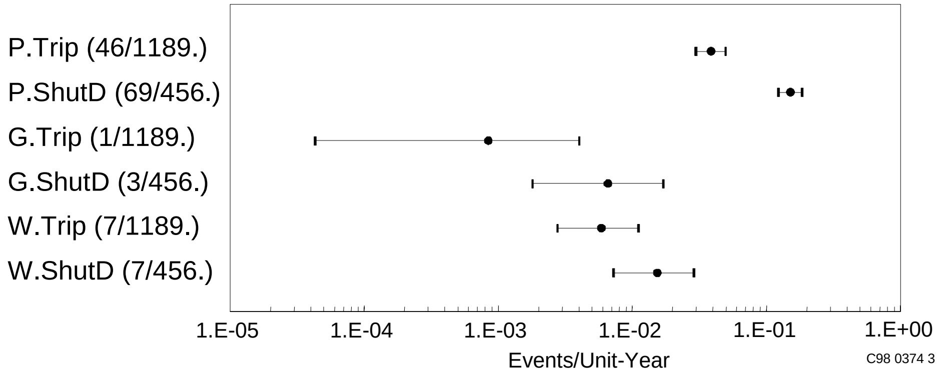

Figure B-1. Frequencies of non-momentary LOSP initiating events and shutdown events. Points are maximum likelihood estimates and intervals are 90% confidence intervals. Units are events per unit critical year and events per unit shutdown year, respectively.

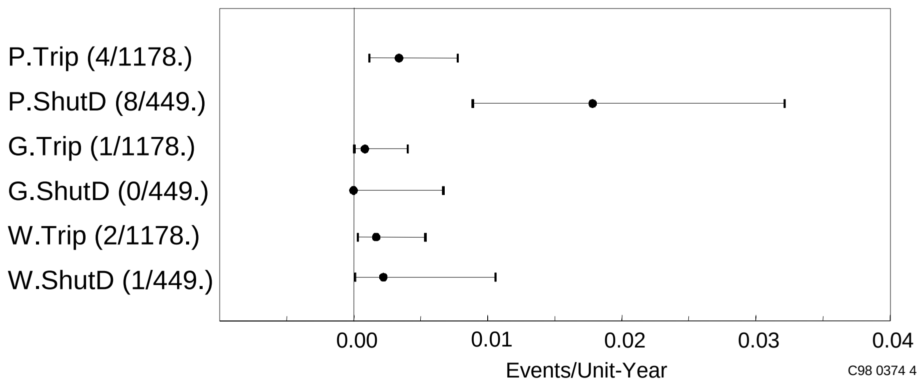

Figure B-2. Frequencies of momentary LOSP initiating events and shutdown events. The labels and symbols have the same meaning as in Figure B-1. Events at Pilgrim are excluded.

The figures show that the reactor status, operating or shutdown, clearly affects the frequencies of plant-centered events. That is, for non-momentary events and also for momentary events, plant-centered events have higher frequencies when the reactor is shut down than when it is operating. *Discuss eng. reasons.*

Table B-1 displays the causes of momentary events. The heading "Reactor at power" has three subclasses. As can be seen, equipment problems dominate the momentary events at power, and human errors dominate the momentary events during shutdown. For the two main headings, "Reactor at power" and "Reactor shutdown," the difference between the three causes is barely statistically significant, with p-value of 0.04. For the subheadings with fewer events, the differences are not significant.

Table B-1. Causes of plant-centered momentary events, excluding Pilgrim.

	Cause			
	Equipment	Extern. Envir.	Human Error	Total
Reactor at power	6	1	1	8
LOSP initiated trip	3	0	1	4
LOSP but no trip	1	1	0	2
Trip preceded LOSP	2	0	0	2
Reactor shutdown	1	1	6	8

Return now to Figure B-1. Severe-weather non-momentary events also show a tendency to be more frequent during shutdown than during power operation, but it is difficult to say whether the difference is statistically significant. The calculated p-value is 0.06, but the calculation assumes independent events, which is not the case for this data set. The *unit* events were dependent, but the *site* events were independent, or nearly so. Although there were 7 momentary unit initiating events and 7 momentary unit shutdown events, there were only 4 momentary *site* initiating events and 6 momentary *site* shutdown events. If site critical years and site shutdown years could be calculated, the data set for site events would presumably show a difference between the estimated initiating event rate and shutdown rate that is more extreme than in Figure B-2, although based on fewer events. Thus, the calculation of p-values is inconclusive. However, for engineering reasons, we believe that non-momentary events occur more frequently during shutdown than during operation. The reasons are the same as for plant-centered events. *OK????* Therefore, the two frequencies are estimated separately.

For grid-related events, and for momentary severe-weather events, too few events have occurred to show any significant pattern. This report breaks severe-weather events into the same classes as plant-centered events, for consistency of presentation. The grid-related events are rare and dependent, and therefore are analyzed only briefly.

In summary, this report analyzes frequencies for the following classes of events:

- Plant-centered non-momentary initiating events during power operation,
- Plant-centered non-momentary events during shutdown
- Plant-centered momentary initiating events during power operation,
- Plant-centered momentary events during shutdown
- Grid-related non-momentary events,
- Grid-related momentary events,
- Severe-weather non-momentary initiating events during power operation,
- Severe-weather non-momentary events during shutdown
- Severe-weather momentary initiating events during power operation,
- Severe-weather momentary events during shutdown

B-2. ESTIMATION OF EVENT FREQUENCIES

First, one must decide how to model the data: whether to model a time trend and whether to model differences between plants.

The analysis steps are given in section A-2 of Appendix A. First, the possibility of differences between years was considered, and the possible presence of a time trend. Next, the data were analyzed for possible differences between plants. If differences are modeled, they should not only be statistically significant; they should also be significant from an engineering standpoint, that is, large enough to have a practical effect. Therefore, when plant-specific frequencies could be estimated, the highest and lowest plant-specific rates were compared, to see if the difference was significant from an engineering perspective. Table B-2 summarizes the results of all the analyses mentioned so far.

Table B-2 mentions p-values. Moderately accurate calculation of p-value requires at least 58 events for analysis by unit and at least 9 events for analysis by year. When p-values based on fewer events are shown, they should be interpreted as extremely rough.

The conclusions on how to treat the data in the analyses are as follows. For non-momentary events:

- Plant-centered initiating events, during operation. Model the extra-Poisson variation between years. The trend is questionable. Use engineering insights to supplement statistical evidence concerning a trend. Present a generic estimate, with no trend modeled, and also present an estimate for 1996 based on a modeled trend. The generic estimate is mathematically equivalent to an empirical Bayes analysis of the year-to-year variation.

Table B-2. Summary of data analyses for frequencies (events per unit-year).

	Events	Betw.-year diffs?	Trend in time?	Betw.-unit diffs?
Non-momentary events				
P-Trip	46	Yes, p-val = 0.009	Minimal: p-val = 0.03 when lack of fit ignored; p-val = 0.11 when lack of fit modeled	No (p-val = 0.4)
P-SD	69	Minimal, p-val = 0.1	No (p-val = 0.3)	Yes (p-val = 0.0000) Emp. Bayes ratio of highest to lowest = 10
G-total	4	Yes, but very few events, which are dependent	Yes, but very few events, which are dependent	Yes, but very few events, which are dependent
W-trip	7	Borderline, p-val = 0.055, caused by dependence of units	Minimal, p-val = 0.09, but calculation assumes independent events	No (p-val = 0.95)
W-SD	7	Yes, p-val = 0.0000, caused by 1993 storm	No (p-val = 0.12), and calc. assumes indep.	Yes (p-val = 0.024)
Momentary events				
P-Trip	4	No (p-val = 0.6)	No (p-val = 0.4)	No (p-val = 0.9)
P-SD	11	No (p-val = 0.8)	No (p-val = 0.5)	Yes, p-val = 0.004), Pilgrim high
G-total	1	No	No	No
W-Trip	4	Borderline, p-val = 0.06, caused by dependence of units	Minimal (p-val = 0.1), calculation influenced by Pilgrim events	Yes, p-val = 0.006, Pilgrim high
W-SD	4	No (p-val = 0.8)	No (p-val = 0.4)	Yes, p-val = 0.006, Pilgrim high
Momentary events, without Pilgrim				
P-Trip	4	No, p-val = 0.6	No, p-val = 0.4	No (p-val = 0.9)
P-SD	8	No, p-val = 0.7	No, p-val = 0.7	Yes, p-val = 0.016, but data set small, and emp. Bayes estimate is degenerate
G-total	1	No	No	No
W-Trip	2	Yes, p-val = 0.001, caused by dependence of units	Model could not be fitted — estimates did not converge	No (p-val = 0.97)
W-SD	1	No	No	No

- Plant-centered events, during shutdown. Pool the data from all the years, and quantify between-plant variation with an empirical Bayes model.

- Grid-related events. Two of the events occurred at one plant (Rancho Seco) in 1981. It seems oversimplified to model the high rate there as a function only of the plant or only of the year; however it is difficult to construct a truly appropriate model. Two other events occurred together at the Turkey Point site, where the grid has since been modified (P. Baranowsky, personal communication). For these reasons, present the data but do not perform a statistical analysis.

- Severe-weather initiating events, during operations. Pool the data from all the years, and calculate a single generic estimate.

- Severe-weather events, during shutdown. Pool the data from all the years, and quantify between-plant variation with an empirical Bayes model.

For momentary events, treat Pilgrim separately. Obtain industry estimates with Pilgrim excluded, as follows.

- Plant-centered events. Calculate a single generic estimate for initiating events during operation, and a single generic estimate for shutdown events.

- Grid-related events. Calculate a single generic estimate, ignoring the operation/shutdown distinction.

- Severe-weather events. Calculate a single generic estimate for initiating events during operation, and a single generic estimate for shutdown events. The reason for distinguishing between operation and shutdown is only for consistency with the plant-centered and non-momentary severe-weather analyses.

Numerical values are shown in Table B-3. Each line refers to a Bayesian distribution for the event frequency. The first three numbers in the line (columns 2 through 4) are the 5th percentile, the mean, and the 95th percentile of the frequency, in units of events per critical year or shutdown year, as relevant.

Each distribution is presented as a distribution form accompanied by two parameters. Gamma distributions are shown in the form gamma(shape parameter, scale parameter), where the shape parameter is unitless and the scale parameter is in unit critical years or unit shutdown years. The mean of the distribution is (shape parameter)/(scale parameter), and the percentiles must be found by a computer calculation. Lognormal distributions are shown in the form lognormal(median, error factor), where the median has units events per unit critical year or events per unit shutdown year, and the error factor is unitless. *Both the median and the mean are given, in different columns; do not confuse them.* The percentiles are related to the other parameters by: 5th percentile = median/(error factor), 95th percentile = median×(error factor). The mean is related by mean = $\exp(\mu + \sigma^2/2)$, with μ = ln(median) and σ = ln(error factor)/1.645.

Table B-3. Event Occurrence Rates: Means, Percentiles, and Distributions. (See text for detailed explanation.)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Plant-centered initiating events during operation				
Non-momentary events (46 unit events; calculated uncertainty accounts for between-year variation, above expected variation of Poisson counts)				
If no trend modeled (recommended)				
Industry	6.39E-3	4.00E-2	9.73E-2	gamma[a](1.844, 46.12 crit. yrs.)
If trend modeled				
Industry, 1996	1.11E-2	2.42E-2	4.44E-2	lognormal[a](2.22E-2, 1.999)
Momentary events (4 events, excluding Pilgrim)				
Industry, 1996	1.41E-3	3.82E-3	7.18E-3	gamma[a](4.500, 1178.4 crit. yrs.)
Plant-centered events during shutdown				
Non-momentary events (69 unit events, between-unit variation modeled)				
Industry	1.07E-2	1.58E-1	4.54E-1	gamma[a](1.127, 7.131 down yrs.)
Arkansas 1	6.37E-3	1.02E-1	2.95E-1	gamma(1.087, 10.70 down yrs.)
Arkansas 2	6.50E-3	1.03E-1	3.01E-1	gamma(1.089, 10.53 down yrs.)
Beaver Valley 1	6.18E-3	9.91E-2	2.88E-1	gamma(1.085, 10.96 down yrs.)
Beaver Valley 2	4.36E-2	2.46E-1	5.85E-1	gamma(1.995, 8.10 down yrs.)
Big Rock Point	3.56E-2	1.92E-1	4.49E-1	gamma(2.075, 10.83 down yrs.)
Braidwood 1	4.09E-2	2.26E-1	5.33E-1	gamma(2.030, 8.98 down yrs.)
Braidwood 2	8.58E-3	1.33E-1	3.86E-1	gamma(1.101, 8.27 down yrs.)
Browns Ferry 1	3.04E-3	5.46E-2	1.61E-1	gamma(1.035, 18.97 down yrs.)
Browns Ferry 2	4.21E-3	7.16E-2	2.10E-1	gamma(1.058, 14.77 down yrs.)
Browns Ferry 3	3.12E-3	5.58E-2	1.65E-1	gamma(1.037, 18.58 down yrs.)
Brunswick 1	2.95E-2	1.56E-1	3.65E-1	gamma(2.099, 13.42 down yrs.)
Brunswick 2	3.06E-2	1.62E-1	3.80E-1	gamma(2.096, 12.90 down yrs.)
Byron 1	7.81E-3	1.22E-1	3.53E-1	gamma(1.098, 9.01 down yrs.)
Byron 2	8.62E-3	1.34E-1	3.87E-1	gamma(1.101, 8.24 down yrs.)
Callaway	8.40E-3	1.30E-1	3.78E-1	gamma(1.101, 8.44 down yrs.)
Calvert Cliffs 1	5.66E-3	9.18E-2	2.68E-1	gamma(1.079, 11.75 down yrs.)
Calvert Cliffs 2	5.85E-3	9.45E-2	2.75E-1	gamma(1.082, 11.45 down yrs.)
Catawba 1	7.22E-3	1.13E-1	3.29E-1	gamma(1.095, 9.65 down yrs.)
Catawba 2	7.71E-3	1.20E-1	3.49E-1	gamma(1.098, 9.12 down yrs.)
Clinton 1	7.48E-3	1.17E-1	3.40E-1	gamma(1.097, 9.36 down yrs.)
Comanche Peak 1	8.71E-3	1.35E-1	3.91E-1	gamma(1.101, 8.16 down yrs.)
Comanche Peak 2	9.21E-3	1.43E-1	4.13E-1	gamma(1.101, 7.72 down yrs.)
Cook 1	6.24E-3	9.99E-2	2.91E-1	gamma(1.086, 10.87 down yrs.)
Cook 2	5.66E-3	9.18E-2	2.68E-1	gamma(1.079, 11.75 down yrs.)
Cooper	5.77E-3	9.34E-2	2.72E-1	gamma(1.081, 11.58 down yrs.)
Crystal River 3	1.96E-1	4.96E-1	9.06E-1	gamma(5.042, 10.17 down yrs.)
Davis-Besse	5.51E-3	8.99E-2	2.62E-1	gamma(1.078, 11.99 down yrs.)
Diablo Canyon 1	8.56E-2	3.41E-1	7.35E-1	gamma(2.742, 8.04 down yrs.)
Diablo Canyon 2	8.15E-3	1.27E-1	3.67E-1	gamma(1.100, 8.68 down yrs.)
Dresden 2	5.41E-3	8.84E-2	2.58E-1	gamma(1.076, 12.18 down yrs.)
Dresden 3	5.38E-3	8.80E-2	2.57E-1	gamma(1.076, 12.23 down yrs.)
Duane Arnold	3.58E-2	1.93E-1	4.52E-1	gamma(2.074, 10.77 down yrs.)
Farley 1	3.89E-2	2.12E-1	5.00E-1	gamma(2.050, 9.66 down yrs.)

Table B-3. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Farley 2	4.12E-2	2.28E-1	5.39E-1	gamma(2.027, 8.88 down yrs.)
Fermi 2	6.14E-3	9.85E-2	2.87E-1	gamma(1.085, 11.02 down yrs.)
Fitzpatrick	5.77E-3	9.33E-2	2.72E-1	gamma(1.081, 11.58 down yrs.)
Fort Calhoun	1.21E-1	3.84E-1	7.67E-1	gamma(3.578, 9.32 down yrs.)
Fort St. Vrain	5.26E-3	8.64E-2	2.52E-1	gamma(1.074, 12.44 down yrs.)
Ginna	6.92E-3	1.09E-1	3.17E-1	gamma(1.092, 10.00 down yrs.)
Grand Gulf	7.67E-3	1.20E-1	3.48E-1	gamma(1.098, 9.16 down yrs.)
Haddam Neck	1.57E-1	4.35E-1	8.25E-1	gamma(4.350, 10.00 down yrs.)
Harris	8.27E-3	1.28E-1	3.72E-1	gamma(1.100, 8.57 down yrs.)
Hatch 1	3.55E-2	1.91E-1	4.47E-1	gamma(2.076, 10.89 down yrs.)
Hatch 2	6.52E-3	1.04E-1	3.02E-1	gamma(1.089, 10.49 down yrs.)
Hope Creek	8.10E-3	1.26E-1	3.65E-1	gamma(1.100, 8.73 down yrs.)
Indian Point 2	1.14E-1	3.55E-1	7.04E-1	gamma(3.682, 10.37 down yrs.)
Indian Point 3	9.23E-2	2.74E-1	5.33E-1	gamma(3.929, 14.36 down yrs.)
Kewaunee	7.37E-3	1.16E-1	3.35E-1	gamma(1.096, 9.48 down yrs.)
La Crosse	1.81E-1	5.45E-1	1.07E+0	gamma(3.852, 7.07 down yrs.)
Lasalle 1	6.32E-3	1.01E-1	2.94E-1	gamma(1.087, 10.77 down yrs.)
Lasalle 2	6.65E-3	1.05E-1	3.07E-1	gamma(1.090, 10.33 down yrs.)
Limerick 1	8.05E-3	1.25E-1	3.63E-1	gamma(1.099, 8.78 down yrs.)
Limerick 2	9.24E-3	1.43E-1	4.15E-1	gamma(1.101, 7.69 down yrs.)
Maine Yankee	6.16E-3	9.87E-2	2.87E-1	gamma(1.085, 10.99 down yrs.)
McGuire 1	3.54E-2	1.90E-1	4.45E-1	gamma(2.077, 10.93 down yrs.)
McGuire 2	3.91E-2	2.14E-1	5.03E-1	gamma(2.049, 9.60 down yrs.)
Millstone 1	3.42E-2	1.83E-1	4.28E-1	gamma(2.083, 11.39 down yrs.)
Millstone 2	3.01E-2	1.60E-1	3.73E-1	gamma(2.097, 13.14 down yrs.)
Millstone 3	6.92E-3	1.09E-1	3.17E-1	gamma(1.092, 9.99 down yrs.)
Monticello	7.85E-2	3.01E-1	6.40E-1	gamma(2.862, 9.52 down yrs.)
Nine Mile Pt. 1	5.12E-3	8.43E-2	2.47E-1	gamma(1.072, 12.71 down yrs.)
Nine Mile Pt. 2	8.20E-2	3.20E-1	6.84E-1	gamma(2.808, 8.79 down yrs.)
North Anna 1	6.19E-3	9.92E-2	2.89E-1	gamma(1.086, 10.94 down yrs.)
North Anna 2	7.19E-3	1.13E-1	3.28E-1	gamma(1.095, 9.68 down yrs.)
Oconee 1	6.83E-3	1.08E-1	3.14E-1	gamma(1.092, 10.11 down yrs.)
Oconee 2	6.96E-3	1.10E-1	3.19E-1	gamma(1.093, 9.94 down yrs.)
Oconee 3	7.67E-2	2.91E-1	6.18E-1	gamma(2.887, 9.91 down yrs.)
Oyster Creek	6.45E-2	2.36E-1	4.94E-1	gamma(3.012, 12.78 down yrs.)
Palisades	6.19E-2	2.25E-1	4.71E-1	gamma(3.030, 13.45 down yrs.)
Palo Verde 1	6.46E-3	1.03E-1	2.99E-1	gamma(1.088, 10.57 down yrs.)
Palo Verde 2	7.04E-3	1.11E-1	3.22E-1	gamma(1.093, 9.85 down yrs.)
Palo Verde 3	7.86E-3	1.23E-1	3.55E-1	gamma(1.099, 8.96 down yrs.)
Peach Bottom 2	2.98E-2	1.58E-1	3.70E-1	gamma(2.098, 13.26 down yrs.)
Peach Bottom 3	2.97E-2	1.58E-1	3.69E-1	gamma(2.098, 13.30 down yrs.)
Perry	6.93E-3	1.09E-1	3.18E-1	gamma(1.092, 9.99 down yrs.)
Pilgrim	6.19E-2	2.25E-1	4.71E-1	gamma(3.030, 13.45 down yrs.)
Point Beach 1	3.95E-2	2.16E-1	5.09E-1	gamma(2.045, 9.47 down yrs.)
Point Beach 2	3.94E-2	2.16E-1	5.08E-1	gamma(2.046, 9.49 down yrs.)
Prairie Island 1	4.18E-2	2.33E-1	5.50E-1	gamma(2.019, 8.68 down yrs.)
Prairie Island 2	7.86E-3	1.23E-1	3.55E-1	gamma(1.099, 8.97 down yrs.)
Quad Cities 1	3.41E-2	1.83E-1	4.28E-1	gamma(2.083, 11.40 down yrs.)
Quad Cities 2	7.05E-2	2.62E-1	5.51E-1	gamma(2.959, 11.31 down yrs.)
Rancho Seco	5.46E-3	8.91E-2	2.60E-1	gamma(1.077, 12.08 down yrs.)
River Bend	7.14E-3	1.12E-1	3.26E-1	gamma(1.094, 9.74 down yrs.)
Robinson 2	5.55E-3	9.04E-2	2.64E-1	gamma(1.078, 11.93 down yrs.)
Salem 1	2.98E-2	1.58E-1	3.69E-1	gamma(2.098, 13.28 down yrs.)
Salem 2	2.98E-2	1.58E-1	3.69E-1	gamma(2.098, 13.27 down yrs.)
San Onofre 1	2.87E-2	1.52E-1	3.55E-1	gamma(2.100, 13.82 down yrs.)
San Onofre 2	7.18E-3	1.13E-1	3.28E-1	gamma(1.094, 9.69 down yrs.)
San Onofre 3	7.36E-3	1.15E-1	3.35E-1	gamma(1.096, 9.49 down yrs.)
Seabrook	8.77E-3	1.36E-1	3.94E-1	gamma(1.101, 8.10 down yrs.)
Sequoyah 1	4.87E-3	8.09E-2	2.37E-1	gamma(1.069, 13.21 down yrs.)
Sequoyah 2	5.46E-3	8.90E-2	2.60E-1	gamma(1.077, 12.09 down yrs.)
South Texas 1	7.21E-3	1.13E-1	3.29E-1	gamma(1.095, 9.65 down yrs.)
South Texas 2	7.63E-3	1.19E-1	3.46E-1	gamma(1.097, 9.20 down yrs.)
St. Lucie 1	6.42E-3	1.02E-1	2.98E-1	gamma(1.088, 10.62 down yrs.)

Table B-3. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
St. Lucie 2	7.86E-3	1.23E-1	3.55E-1	gamma(1.099, 8.97 down yrs.)
Summer	7.57E-3	1.18E-1	3.43E-1	gamma(1.097, 9.27 down yrs.)
Surry 1	6.06E-3	9.74E-2	2.84E-1	gamma(1.084, 11.13 down yrs.)
Surry 2	6.12E-3	9.82E-2	2.86E-1	gamma(1.085, 11.04 down yrs.)
Susquehanna 1	7.17E-3	1.13E-1	3.27E-1	gamma(1.094, 9.70 down yrs.)
Susquehanna 2	7.80E-3	1.22E-1	3.53E-1	gamma(1.098, 9.03 down yrs.)
Three Mile Isl 1	5.01E-3	8.29E-2	2.43E-1	gamma(1.071, 12.91 down yrs.)
Trojan	5.63E-3	9.15E-2	2.67E-1	gamma(1.079, 11.80 down yrs.)
Turkey Point 3	6.61E-2	2.42E-1	5.09E-1	gamma(2.999, 12.37 down yrs.)
Turkey Point 4	3.14E-2	1.67E-1	3.91E-1	gamma(2.094, 12.52 down yrs.)
Vermont Yankee	3.87E-2	2.11E-1	4.96E-1	gamma(2.052, 9.73 down yrs.)
Vogtle 1	4.46E-2	2.54E-1	6.05E-1	gamma(1.979, 7.79 down yrs.)
Vogtle 2	9.16E-3	1.42E-1	4.11E-1	gamma(1.102, 7.76 down yrs.)
Wash. Nuclear 2	3.67E-2	1.98E-1	4.64E-1	gamma(2.068, 10.45 down yrs.)
Waterford 3	7.93E-3	1.24E-1	3.58E-1	gamma(1.099, 8.89 down yrs.)
Watts Bar 1	9.96E-3	1.55E-1	4.49E-1	gamma(1.099, 7.09 down yrs.)
Wolf Creek	4.16E-2	2.31E-1	5.46E-1	gamma(2.022, 8.76 down yrs.)
Yankee-Rowe	3.99E-2	2.19E-1	5.16E-1	gamma(2.041, 9.32 down yrs.)
Zion 1	5.34E-3	8.75E-2	2.56E-1	gamma(1.075, 12.29 down yrs.)
Zion 2	3.26E-2	1.74E-1	4.06E-1	gamma(2.090, 12.05 down yrs.)
Momentary events (8 events, excluding Pilgrim)				
Industry	9.66E-3	1.89E-2	3.07E-2	gamma[a](8.500, 449.0 crit. yrs.)
Grid-related events				
Non-momentary events. The 3 shutdown events and one initiating event consisted of only three site events at two sites. All the grid-related events are listed in Table C-2. Because of the strong dependencies, the possibility of plant-specific differences, and the possibility of a trend in time, no statistical analysis is performed.				
Momentary events. One momentary event occurred in 1627 unit calendar years (excluding Pilgrim).				
Industry	1.08E-4	9.22E-4	2.40E-3	gamma[a](1.500, 1627.3 crit. yrs.)
Severe-weather initiating events during operation				
Non-momentary events (7 unit events)				
Industry	3.05E-3	6.31E-3	1.05E-2	gamma[a](7.500, 1188.6 crit. yrs.)
Momentary events (2 unit events, excluding Pilgrim)				
Industry	4.86E-4	2.12E-3	4.70E-3	gamma[a](2.500, 1178.4 crit. yrs.)
Severe-weather events during shutdown				
Non-momentary events (7 unit events)				
Industry	<1.E-10	1.42E-2	8.05E-2	gamma[a](0.126, 8.876 down yrs.)
Arkansas 1	<1.E-10	9.82E-3	5.59E-2	gamma(0.122, 12.47 down yrs.)
Arkansas 2	<1.E-10	9.97E-3	5.67E-2	gamma(0.122, 12.28 down yrs.)
Beaver Valley 1	<1.E-10	9.60E-3	5.47E-2	gamma(0.122, 12.73 down yrs.)
Beaver Valley 2	<1.E-10	1.21E-2	6.90E-2	gamma(0.123, 10.13 down yrs.)
Big Rock Point	<1.E-10	9.81E-3	5.58E-2	gamma(0.122, 12.48 down yrs.)
Braidwood 1	<1.E-10	1.13E-2	6.43E-2	gamma(0.123, 10.88 down yrs.)
Braidwood 2	<1.E-10	1.23E-2	7.02E-2	gamma(0.123, 9.96 down yrs.)
Browns Ferry 1	<1.E-10	5.63E-3	3.22E-2	gamma(0.119, 21.06 down yrs.)

Table B-3. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Browns Ferry 2	<1.E-10	7.21E-3	4.11E-2	gamma(0.120, 16.70 down yrs.)
Browns Ferry 3	<1.E-10	5.74E-3	3.28E-2	gamma(0.119, 20.67 down yrs.)
Brunswick 1	2.03E-3	7.34E-2	2.38E-1	gamma(0.803, 10.94 down yrs.)
Brunswick 2	1.95E-3	7.59E-2	2.48E-1	gamma(0.784, 10.33 down yrs.)
Byron 1	<1.E-10	1.15E-2	6.52E-2	gamma(0.123, 10.72 down yrs.)
Byron 2	<1.E-10	1.24E-2	7.05E-2	gamma(0.123, 9.92 down yrs.)
Callaway	<1.E-10	1.21E-2	6.90E-2	gamma(0.123, 10.13 down yrs.)
Calvert Cliffs 1	<1.E-10	8.99E-3	5.12E-2	gamma(0.122, 13.56 down yrs.)
Calvert Cliffs 2	<1.E-10	9.22E-3	5.25E-2	gamma(0.122, 13.24 down yrs.)
Catawba 1	<1.E-10	1.08E-2	6.14E-2	gamma(0.123, 11.38 down yrs.)
Catawba 2	<1.E-10	1.13E-2	6.45E-2	gamma(0.123, 10.83 down yrs.)
Clinton 1	<1.E-10	1.11E-2	6.31E-2	gamma(0.123, 11.07 down yrs.)
Comanche Peak 1	<1.E-10	1.25E-2	7.10E-2	gamma(0.123, 9.84 down yrs.)
Comanche Peak 2	<1.E-10	1.31E-2	7.44E-2	gamma(0.123, 9.39 down yrs.)
Cook 1	<1.E-10	9.68E-3	5.51E-2	gamma(0.122, 12.64 down yrs.)
Cook 2	<1.E-10	8.99E-3	5.12E-2	gamma(0.122, 13.56 down yrs.)
Cooper	<1.E-10	9.12E-3	5.19E-2	gamma(0.122, 13.37 down yrs.)
Crystal River 3	1.62E-2	2.22E-1	6.29E-1	gamma(1.167, 5.26 down yrs.)
Davis-Besse	<1.E-10	8.82E-3	5.02E-2	gamma(0.122, 13.81 down yrs.)
Diablo Canyon 1	<1.E-10	1.16E-2	6.57E-2	gamma(0.123, 10.64 down yrs.)
Diablo Canyon 2	<1.E-10	1.19E-2	6.74E-2	gamma(0.123, 10.37 down yrs.)
Dresden 2	<1.E-10	8.69E-3	4.95E-2	gamma(0.122, 14.00 down yrs.)
Dresden 3	<1.E-10	8.66E-3	4.93E-2	gamma(0.122, 14.05 down yrs.)
Duane Arnold	<1.E-10	9.86E-3	5.61E-2	gamma(0.122, 12.42 down yrs.)
Farley 1	<1.E-10	1.07E-2	6.10E-2	gamma(0.123, 11.46 down yrs.)
Farley 2	<1.E-10	1.14E-2	6.48E-2	gamma(0.123, 10.79 down yrs.)
Fermi 2	<1.E-10	9.56E-3	5.44E-2	gamma(0.122, 12.79 down yrs.)
Fitzpatrick	<1.E-10	9.12E-3	5.19E-2	gamma(0.122, 13.38 down yrs.)
Fort Calhoun	<1.E-10	1.01E-2	5.74E-2	gamma(0.123, 12.15 down yrs.)
Fort St. Vrain	1.94E-3	7.61E-2	2.49E-1	gamma(0.783, 10.28 down yrs.)
Ginna	<1.E-10	1.04E-2	5.94E-2	gamma(0.123, 11.74 down yrs.)
Grand Gulf	<1.E-10	1.13E-2	6.43E-2	gamma(0.123, 10.87 down yrs.)
Haddam Neck	<1.E-10	9.32E-3	5.30E-2	gamma(0.122, 13.11 down yrs.)
Harris	<1.E-10	1.20E-2	6.82E-2	gamma(0.123, 10.26 down yrs.)
Hatch 1	<1.E-10	9.77E-3	5.56E-2	gamma(0.122, 12.53 down yrs.)
Hatch 2	<1.E-10	1.00E-2	5.69E-2	gamma(0.122, 12.25 down yrs.)
Hope Creek	<1.E-10	1.18E-2	6.71E-2	gamma(0.123, 10.43 down yrs.)
Indian Point 2	<1.E-10	9.43E-3	5.37E-2	gamma(0.122, 12.96 down yrs.)
Indian Point 3	<1.E-10	7.49E-3	4.27E-2	gamma(0.121, 16.12 down yrs.)
Kewaunee	<1.E-10	1.10E-2	6.24E-2	gamma(0.123, 11.20 down yrs.)
La Crosse	<1.E-10	1.13E-2	6.43E-2	gamma(0.123, 10.88 down yrs.)
Lasalle 1	<1.E-10	9.76E-3	5.56E-2	gamma(0.122, 12.53 down yrs.)
Lasalle 2	<1.E-10	1.01E-2	5.77E-2	gamma(0.123, 12.09 down yrs.)
Limerick 1	<1.E-10	1.17E-2	6.67E-2	gamma(0.123, 10.48 down yrs.)
Limerick 2	<1.E-10	1.31E-2	7.46E-2	gamma(0.123, 9.37 down yrs.)
Maine Yankee	<1.E-10	9.58E-3	5.45E-2	gamma(0.122, 12.77 down yrs.)
McGuire 1	<1.E-10	9.74E-3	5.54E-2	gamma(0.122, 12.56 down yrs.)
McGuire 2	<1.E-10	1.08E-2	6.12E-2	gamma(0.123, 11.40 down yrs.)
Millstone 1	<1.E-10	9.42E-3	5.36E-2	gamma(0.122, 12.97 down yrs.)
Millstone 2	<1.E-10	8.36E-3	4.76E-2	gamma(0.121, 14.53 down yrs.)
Millstone 3	<1.E-10	1.05E-2	5.95E-2	gamma(0.123, 11.73 down yrs.)
Monticello	<1.E-10	1.04E-2	5.90E-2	gamma(0.123, 11.82 down yrs.)
Nine Mile Pt. 1	<1.E-10	8.34E-3	4.75E-2	gamma(0.121, 14.56 down yrs.)
Nine Mile Pt. 2	<1.E-10	1.09E-2	6.22E-2	gamma(0.123, 11.24 down yrs.)
North Anna 1	<1.E-10	9.62E-3	5.47E-2	gamma(0.122, 12.72 down yrs.)
North Anna 2	<1.E-10	1.08E-2	6.12E-2	gamma(0.123, 11.41 down yrs.)
Oconee 1	<1.E-10	1.03E-2	5.89E-2	gamma(0.123, 11.85 down yrs.)
Oconee 2	<1.E-10	1.05E-2	5.98E-2	gamma(0.123, 11.68 down yrs.)
Oconee 3	<1.E-10	1.01E-2	5.75E-2	gamma(0.123, 12.13 down yrs.)
Oyster Creek	<1.E-10	8.39E-3	4.78E-2	gamma(0.121, 14.47 down yrs.)
Palisades	<1.E-10	8.06E-3	4.59E-2	gamma(0.121, 15.03 down yrs.)
Palo Verde 1	<1.E-10	9.93E-3	5.65E-2	gamma(0.122, 12.33 down yrs.)
Palo Verde 2	<1.E-10	1.06E-2	6.03E-2	gamma(0.123, 11.59 down yrs.)

Table B-3. (continued)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Palo Verde 3	<1.E-10	1.15E-2	6.56E-2	gamma(0.123, 10.66 down yrs.)
Peach Bottom 2	<1.E-10	8.30E-3	4.73E-2	gamma(0.121, 14.63 down yrs.)
Peach Bottom 3	<1.E-10	8.28E-3	4.72E-2	gamma(0.121, 14.67 down yrs.)
Perry	<1.E-10	1.05E-2	5.95E-2	gamma(0.123, 11.73 down yrs.)
Pilgrim	2.07E-3	7.21E-2	2.32E-1	gamma(0.813, 11.28 down yrs.)
Point Beach 1	<1.E-10	1.09E-2	6.19E-2	gamma(0.123, 11.29 down yrs.)
Point Beach 2	<1.E-10	1.09E-2	6.18E-2	gamma(0.123, 11.31 down yrs.)
Prairie Island 1	<1.E-10	1.16E-2	6.59E-2	gamma(0.123, 10.62 down yrs.)
Prairie Island 2	<1.E-10	1.15E-2	6.55E-2	gamma(0.123, 10.67 down yrs.)
Quad Cities 1	<1.E-10	9.41E-3	5.36E-2	gamma(0.122, 12.98 down yrs.)
Quad Cities 2	<1.E-10	9.20E-3	5.24E-2	gamma(0.122, 13.26 down yrs.)
Rancho Seco	<1.E-10	8.76E-3	4.99E-2	gamma(0.122, 13.90 down yrs.)
River Bend	<1.E-10	1.07E-2	6.09E-2	gamma(0.123, 11.47 down yrs.)
Robinson 2	<1.E-10	8.87E-3	5.05E-2	gamma(0.122, 13.74 down yrs.)
Salem 1	<1.E-10	8.29E-3	4.72E-2	gamma(0.121, 14.65 down yrs.)
Salem 2	<1.E-10	8.29E-3	4.72E-2	gamma(0.121, 14.64 down yrs.)
San Onofre 1	<1.E-10	8.01E-3	4.56E-2	gamma(0.121, 15.13 down yrs.)
San Onofre 2	<1.E-10	1.07E-2	6.12E-2	gamma(0.123, 11.42 down yrs.)
San Onofre 3	<1.E-10	1.10E-2	6.23E-2	gamma(0.123, 11.21 down yrs.)
Seabrook	<1.E-10	1.26E-2	7.15E-2	gamma(0.123, 9.78 down yrs.)
Sequoyah 1	<1.E-10	8.04E-3	4.58E-2	gamma(0.121, 15.08 down yrs.)
Sequoyah 2	<1.E-10	8.75E-3	4.98E-2	gamma(0.122, 13.91 down yrs.)
South Texas 1	<1.E-10	1.08E-2	6.14E-2	gamma(0.123, 11.38 down yrs.)
South Texas 2	<1.E-10	1.13E-2	6.41E-2	gamma(0.123, 10.91 down yrs.)
St. Lucie 1	<1.E-10	9.89E-3	5.63E-2	gamma(0.122, 12.38 down yrs.)
St. Lucie 2	<1.E-10	1.15E-2	6.55E-2	gamma(0.123, 10.67 down yrs.)
Summer	<1.E-10	1.12E-2	6.37E-2	gamma(0.123, 10.98 down yrs.)
Surry 1	<1.E-10	9.46E-3	5.39E-2	gamma(0.122, 12.91 down yrs.)
Surry 2	<1.E-10	9.54E-3	5.43E-2	gamma(0.122, 12.82 down yrs.)
Susquehanna 1	<1.E-10	1.07E-2	6.11E-2	gamma(0.123, 11.43 down yrs.)
Susquehanna 2	<1.E-10	1.14E-2	6.51E-2	gamma(0.123, 10.74 down yrs.)
Three Mile Isl 1	<1.E-10	8.22E-3	4.68E-2	gamma(0.121, 14.76 down yrs.)
Trojan	<1.E-10	8.96E-3	5.10E-2	gamma(0.122, 13.60 down yrs.)
Turkey Point 3	<1.E-10	8.61E-3	4.90E-2	gamma(0.122, 14.13 down yrs.)
Turkey Point 4	<1.E-10	8.71E-3	4.96E-2	gamma(0.122, 13.97 down yrs.)
Vermont Yankee	<1.E-10	1.07E-2	6.06E-2	gamma(0.123, 11.52 down yrs.)
Vogtle 1	<1.E-10	1.25E-2	7.09E-2	gamma(0.123, 9.86 down yrs.)
Vogtle 2	<1.E-10	1.30E-2	7.40E-2	gamma(0.123, 9.44 down yrs.)
Wash. Nuclear 2	<1.E-10	1.01E-2	5.74E-2	gamma(0.123, 12.15 down yrs.)
Waterford 3	<1.E-10	1.16E-2	6.60E-2	gamma(0.123, 10.60 down yrs.)
Watts Bar 1	<1.E-10	1.40E-2	7.96E-2	gamma(0.122, 8.76 down yrs.)
Wolf Creek	<1.E-10	1.15E-2	6.54E-2	gamma(0.123, 10.68 down yrs.)
Yankee-Rowe	<1.E-10	1.10E-2	6.26E-2	gamma(0.123, 11.17 down yrs.)
Zion 1	<1.E-10	8.62E-3	4.91E-2	gamma(0.122, 14.12 down yrs.)
Zion 2	<1.E-10	9.00E-3	5.13E-2	gamma(0.122, 13.55 down yrs.)
Momentary events (1 unit event, excluding Pilgrim)				
Industry	3.92E-4	3.34E-3	8.70E-3	gamma[a](1.500, 449.0 down yrs.)

a. As explained in the text, the parameters shown for the gamma distribution are the shape parameter and the scale parameter, and those for the lognormal distribution are the *median* and the error factor.

For two data sets, between-plant variation was modeled. The plant-specific frequencies are shown in Figures B-3 and B-4, arranged from the highest frequency to the lowest.

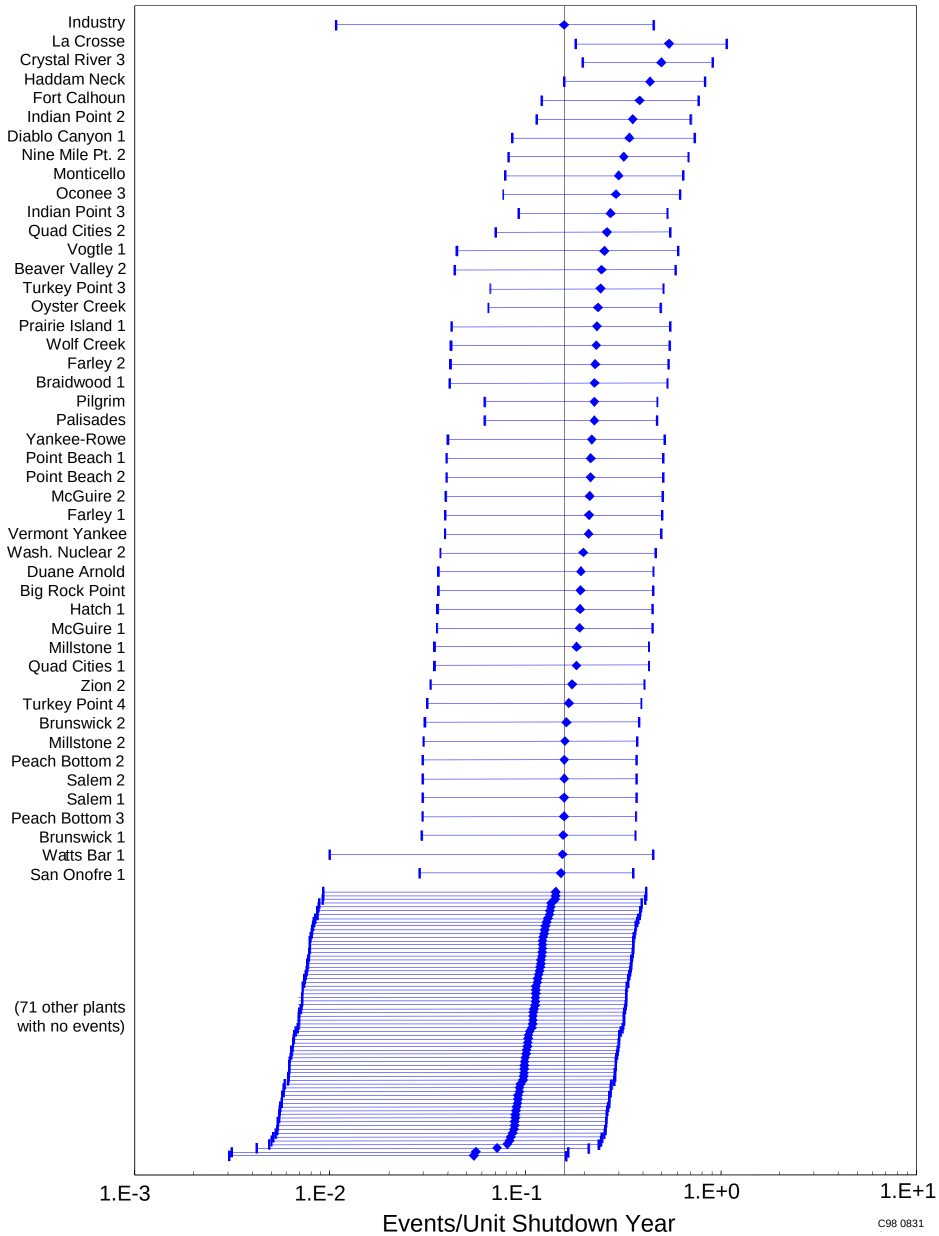

Figure B-3. Frequency of plant-centered LOSP non-momentary events during shutdown. The empirical Bayes estimate and 90% uncertainty interval are shown for each unit.

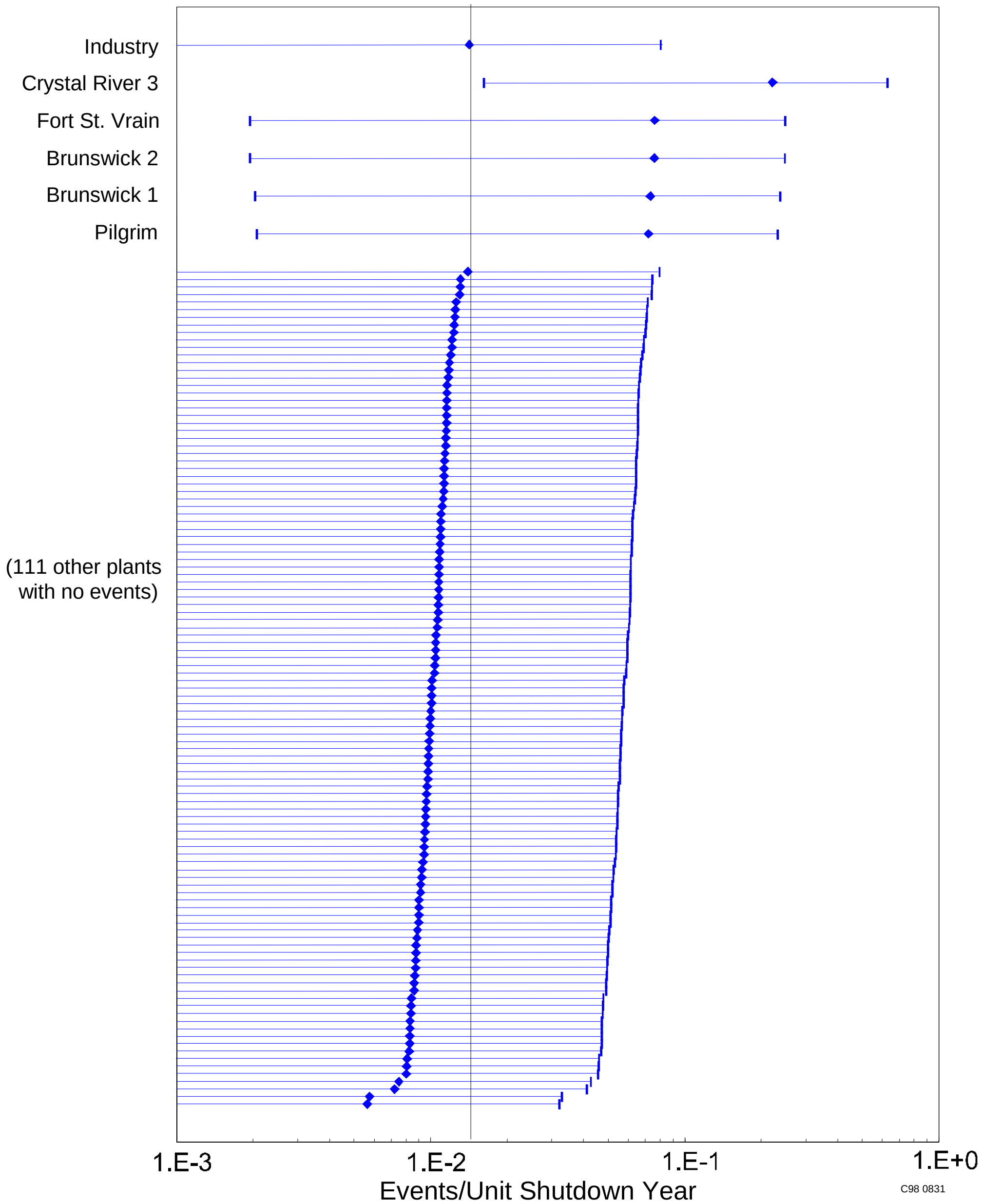

Figure B-4. Frequency of severe-weather LOSP non-momentary events during shutdown. The empirical Bayes estimate and 90% uncertainty interval are shown for each plant unit. The left ends of many intervals extend far to the left of the visible portion of the figure, and are not meaningful.

Figures B-5 through B-9 show the frequencies of the non-momentary events, by year. The dots and vertical lines are maximum likelihood estimates and 90% confidence intervals, based on assumed Poisson data for a single year. The fitted trend line is shown for the plant-centered data, even though the trend is not statistically significant. No trend lines are shown in the other plots, for reasons explained with each figure.

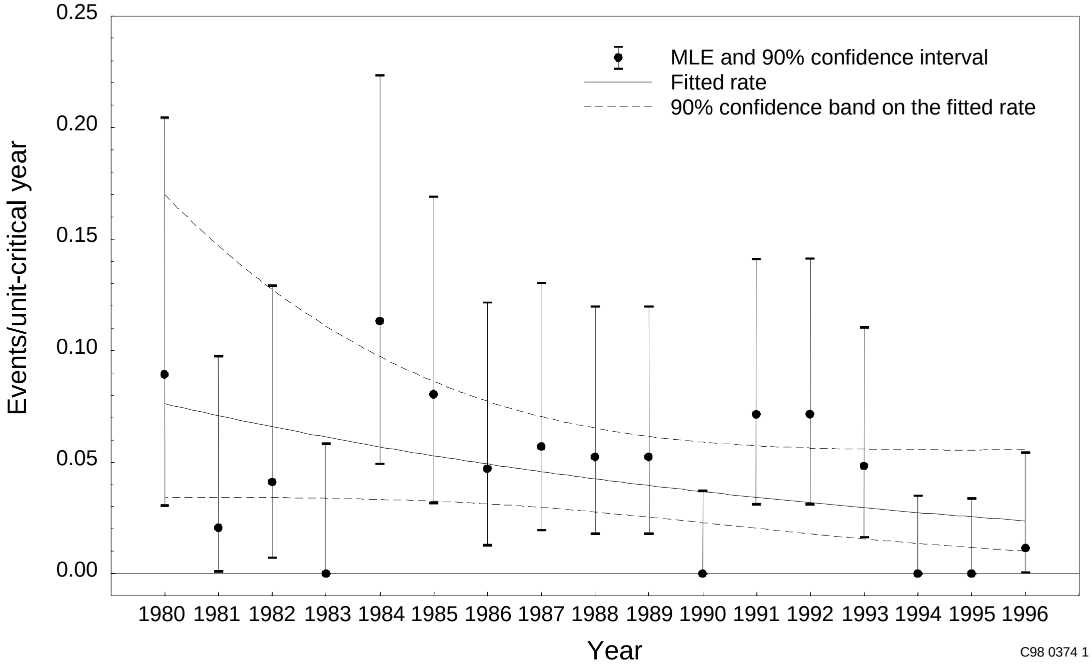

Figure B-5. Frequency of plant-centered LOSP non-momentary initiating events during operation. When the extra-Poisson scatter is accounted for, the trend is not statistically significant (p-value = 0.11).

Figure B-6. Frequency of plant-centered LOSP non-momentary events during shutdown. No trend is fitted, because it is not close to statistically significant. Between-unit variation is present, but the confidence intervals for each year ignore this.

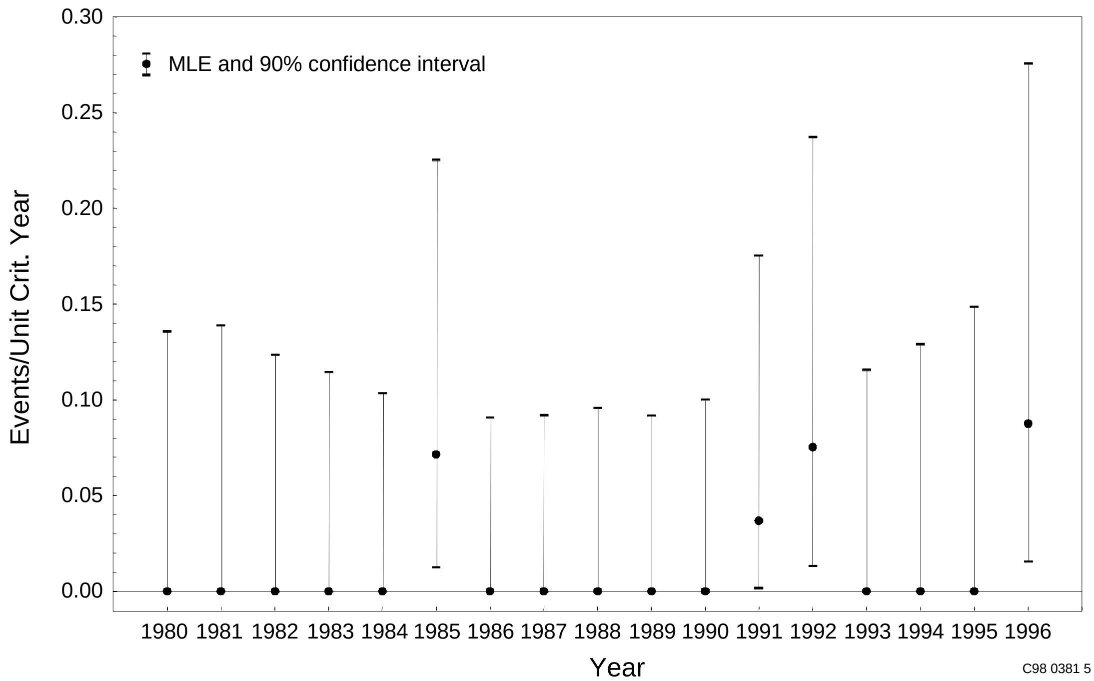

Figure B-7. Frequency of severe-weather LOSP non-momentary initiating events during operation. Any apparent trend is illusory, caused by weather events that affected multiple units at a site in a single year.

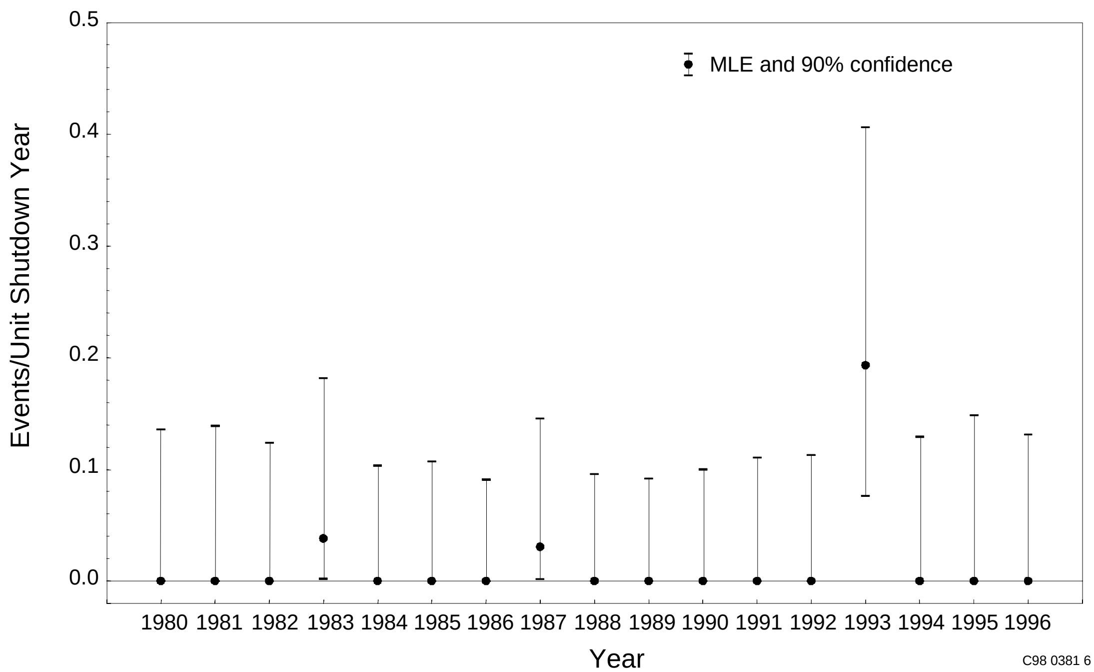

Figure B-8. Frequency of severe-weather LOSP non-momentary events during shutdown. No trend is fitted, because it is not statistically significant. The large frequency in 1993 is the result of a single storm affecting several plants. The confidence intervals for each year ignore between-plant variation.

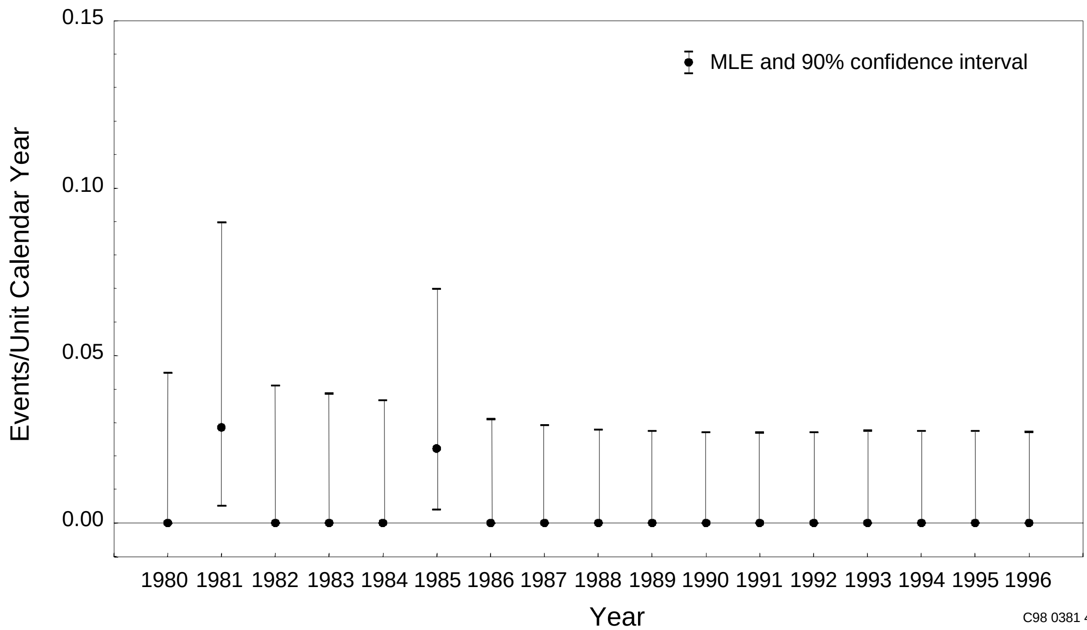

Figure B-9. Frequency of grid-related LOSP non-momentary events, both initiating events and shutdown events. No trend is fitted, because the dependence of events makes it infeasible to determine its statistical significance.

B-3. PRELIMINARY ANALYSIS OF RECOVERY TIMES

This section considers only the non-momentary recovery times. The momentary recovery times are all approximately one minute, and do not need analysis.

To decide on the data subsets that should be analyzed separately, the non-momentary recovery times were compared. Initially, all the recovery times were counted separately. Later, it was observed that when an event causes LOSP at multiple units, the recovery times tend to be similar. In fact, the variation between units from a single event is extremely small compared to the variation between events or the variation between sites. It was decided to eliminate the statistical dependence between recovery times by averaging the recovery times whenever a single event caused LOSP at more than one plant unit.

Therefore, the initial examination was redone, using only the average recovery time if the event caused LOSP at more than one unit. Those results are presented here. Recall that the data have three 1032-categories, four causes, and three plant conditions, shown here with self-explanatory abbreviations.

1032 Category		
	P	plant-centered
	G	grid-related
	W	severe weather
Causes		
	ExtEnv	external environment (typically lightning)
	Equip	equipment problem
	Human	human error
	Other	Other
Plant Conditions		
	Power	power-operation (reactor was at power and did not trip)
	ShutD	shutdown (reactor was shut down during when LOSP occurred)
	Trip	trip (reactor tripped, typically as a result of the LOSP)

B-3.1 Plant-Centered Events

Consider first only the plant-centered events. Figure B-10 shows box plots of the recovery times for three classes of events: trip events, shutdown events, and power-operation events. Shutdown events tend to have somewhat shorter recovery times than trip events. The difference is not statistically significant, however. (The p-value is 0.3 by the Wilcoxon or Kruskal-Wallis test, and 0.4 by the less powerful Kolmogorov-Smirnov test.). For this analysis, the trip events included the four non-initiators, in which the trip preceded the LOSP. These recovery times did not appear different from those of other trip events, and engineering considerations suggested that the recovery time would not depend on which came first, the LOSP or the trip.

The power-operation events, in which the unit did not trip after LOSP, tended to have longer recovery times, and the difference is statistically significant. An engineering explanation is that personnel will act very deliberately, to prevent a trip, if the unit is running without offsite power. Therefore, recovery times are not characterized for power-operation events. They would require separate analysis, and were deemed not of great interest. They were used for the following investigation of causes, because the cause was considered to be independent of the unit response.

To investigate whether any more noteworthy differences can be found, the different causes of the classes of events was reviewed, as shown in Table B-4. This table demonstrates that shutdown events have a high fraction of human error causes (over 50%), whereas trip events have a high fraction of equipment causes (over 50%). This finding is similar to that for momentary events in Table B-1. The recovery times were investigated to determine whether the different causes correspond to different recovery times. The equipment problems have a slightly longer median recovery time, but a box plot shows that the three primary causes have almost identical distributions of recovery time; the differences are not close to statistically significant. Because this investigation did not reveal any interesting patterns, the box plot is not shown.

More differences are seen when the event cause is considered separately for each plant condition. This comparison is given in Figure B-11. Even here, however, the differences are not statistically significant.

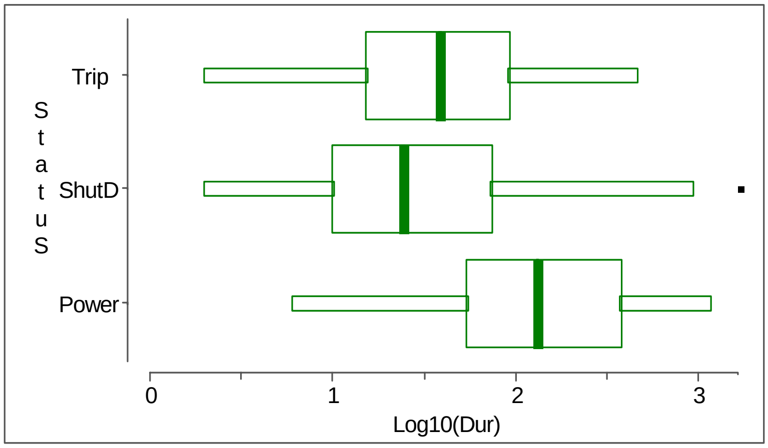

Figure B-10. Logarithms of non-momentary recovery times, for three classes of plant-centered events. The power-operation recovery times are longer than each of the other groups of recovery times, to a statistically significant degree. The difference between trip and shutdown times is not statistically significant (p-val. = 0.3).

Table B-4. Number of plant-centered non-momentary events for each cause and plant status (including events for which recovery times not reported.)

	Equipment	Ext. Envir.	Human	Other	Total
Power	4 (44%)	4 (33%)	1 (11%)	0	9
Shutdown	24 (35%)	5 (7%)	39 (57%)	0	68
Trip	25 (59%)	6 (13%)	13 (29%)	1 (2%)	45
Total	53 (43%)	15 (12%)	53 (43%)	1 (1%)	122

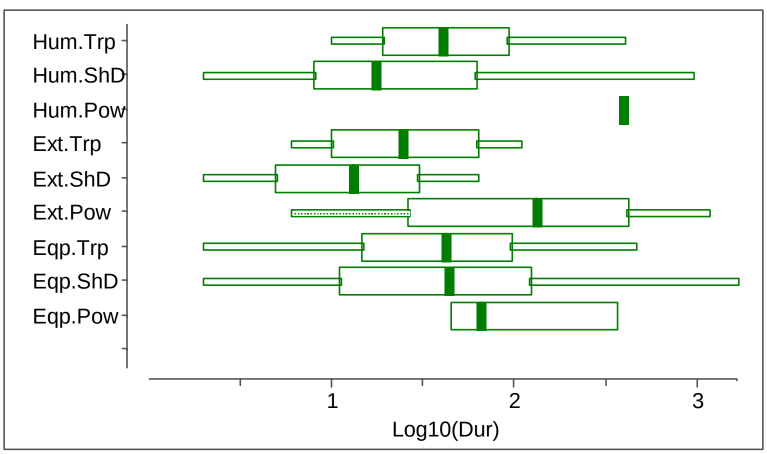

Figure B-11. Logarithms of non-momentary recovery times of plant-centered events, for combinations of event cause and plant condition. The differences are not statistically significant, although when combined as in Figure B-10 some differences are statistically significant.

In summary, plant-centered non-momentary events do not show any strong correspondence with particular causes. Therefore, plant-centered shutdown and initiating events are pooled for analysis of recovery times. The four events for which the trip preceded the LOSP are included in the data. Power-operation events are not used.

B-3.2 Grid-Related and Severe-Weather Events

Figure B-12 shows $\log_{10}$(recovery time) for grid-related events (labeled G) and severe-weather events (labeled W), with shutdown and trip events distinguished. There were no power-operation events in the data. The grid related events have only two trip times and three shutdown times. The data set is too small for the significance calculations to be accurate. For weather events, the difference between trip events and shutdown events is not statistically significant (the p-value is 0.3 for the Wilcoxon and Kruskal-Wallis tests, and 0.6 for the Kolmogorov-Smirnov test.) If a difference exists, there is not enough evidence to reveal the difference clearly. Therefore, for analysis of recovery times for severe-weather events and for recovery times of grid-related events, no distinction was made between shutdown and trip conditions.

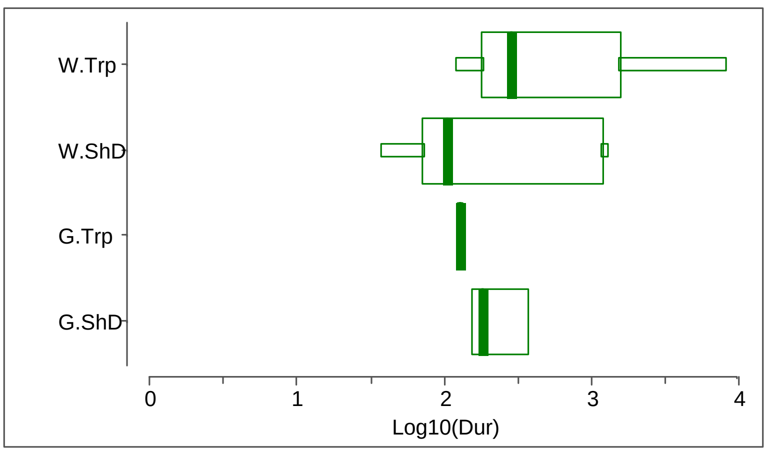

Figure B-12. Logarithms of non-momentary recovery times, for severe-weather events and grid-related events. Among the severe-weather events the difference between trip events and shutdown events is not statistically significant (p-val. > 0.3). The grid-related data set is too small to allow determination of statistical significance.

B-3.3 Summary: The Three Groups Identified Above

Sections B-3.1 and B-3.2 conclude that each 1032-category of events can be analyzed without splitting it further. Therefore, the three groups for analysis are:

- Plant-centered events, excluding power-operation events.
- Grid-related events, and
- Severe-weather events.

The logs of the non-momentary recovery times are shown in Figure B-13. The trip events and shutdown events are combined in this plot, and the power-operation events are excluded, based on the above findings that the trip and shutdown non-momentary events have similar recovery times.

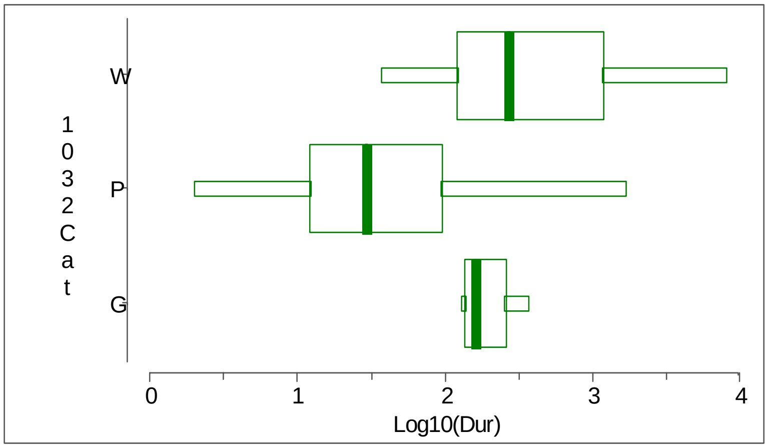

Figure B-13. Logarithms of non-momentary recovery times for the three 1032-categories of events whose recoveries are analyzed separately. The difference between severe-weather and plant-centered times is statistically extremely significant.

The difference between severe-weather and plant-centered recovery times is statistically extremely significant, by either the Wilcoxon test or the Kruskal-Wallis test, with p-value of 0.0003. There are too few grid-related events to allow accurate calculation of a p-value.

As mentioned above, the recovery times are analyzed by site, because when a single event caused LOSP at two units, the two recovery times were usually similar. The counts of events used for analyzing recovery times are given in Table B-5. These counts exclude power-operation events, events when the unit experienced LOSP but the reactor did not trip.

Table B-5. Site events used for analyzing non-momentary recovery times.

	Site Events	Reported Recovery Times
Plant-centered	111	102
Grid-related	4	4
Severe weather	10	9

B-4. ESTIMATION OF DISTRIBUTIONS OF RECOVERY TIMES

B-4.1 Possibility of Time Trends

For plant-centered, grid-related, and severe-weather events, the log(recovery time) was plotted against the event date. Logarithms were used because the distribution of log(recovery time) is roughly symmetrical, whereas the distribution of recovery time is highly skewed. As discussed in section B-4.2 below, it was eventually decided to average the recovery times for a single event affecting two units. The plots considered here, log(recovery time) versus event date, are based on these averaged times for each site event. Figures B-14 through B-16 show the three cases.

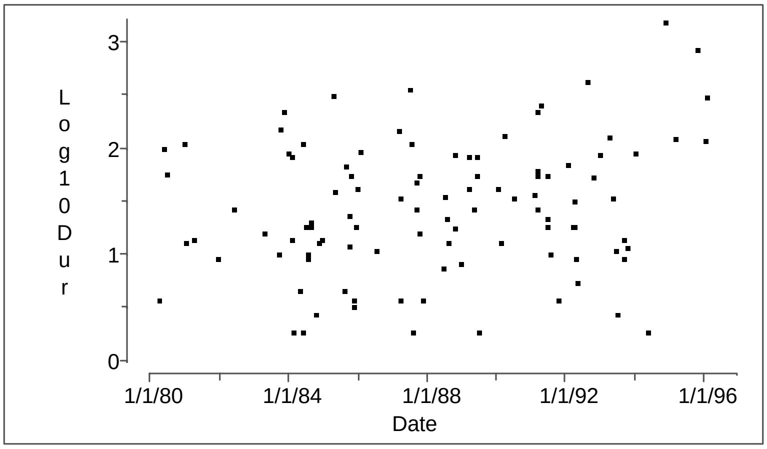

Figure B-14. For non-momentary plant-centered events, plot of $\log_{10}$(recovery time) against event date. A slight upward trend is statistically significant (p-value = 0.03), but is not modeled for reasons discussed in the text.

A statistically significant (p-value = 0.03) trend can be fitted to the data. It is slight: over 17 years, the fitted slope corresponds to an increase in the median recovery time by a factor of 3.6. The plot shows that the trend appears to be a result of an absence of events in the upper left and lower right, and the presence of two large values in the upper right. Indeed, if either of the two highest points in the upper right were dropped, the p-value would rise to 0.08, not quite statistically significant. If both were dropped, the p-value would rise to 0.19, indicating virtually no evidence of a trend.

To see if the trend had an engineering basis, we reexamined the events corresponding to the two largest times in the upper right of Fig. B-14. One event had duration 917 minutes (LER 27595014). Based on engineering considerations, that event could have happened at any time. Nothing makes such an event more likely in recent years than in the early years. The other event lasted for 1675 minutes (LER 31194014). However, the LER states “vital buses were maintained powered from [their diesels]…, to permit adequate assessment of the event prior to restoring offsite power.” The actual time to recovery was coded in the data, because the narrative does not state when offsite power could have been restored. However, the narrative suggests that recovery could have been accomplished sooner if the diesel generators had failed.

The evidence for a trend is very sensitive to one or two values, it is not strongly supported by engineering considerations, and the magnitude of the trend is small. Therefore, this report does not model a time trend for plant-centered recovery times.

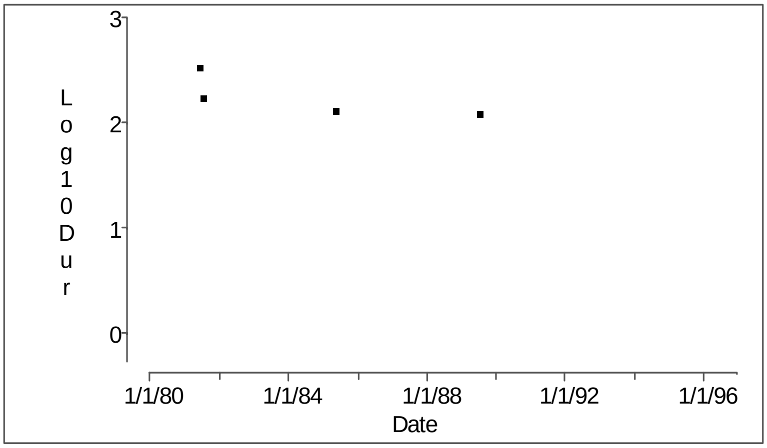

Figure B-15. For non-momentary grid-related events, plot of $\log_{10}$(recovery time) against event date. There is no visible trend.

The grid-related events are rare, and the two events in 1981 may be dependent. This complicates the calculation of a p-value. However, it is evident from the plot that no trend is present.

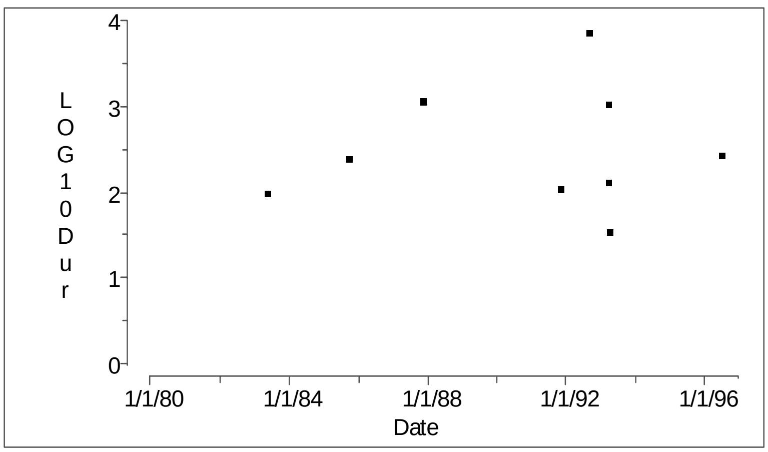

Figure B-16. For non-momentary severe-weather events, plot of $\log_{10}$(recovery time) against event date. There is no statistically significant trend.

B-4.2 Components of Variance

The work presented above in sections B-3 and B-4.1 always used the average recovery time, if a single event affected multiple units at one site. The results presented in this section justify the above use of average times. It begins by using the individual recovery times at the plants, and concludes that those times should be averaged when a single event causes LOSP at multiple units of a site.

Components of variance were estimated, following Model (A-1) of Appendix A. This model equation is repeated here, for convenience of discussion:

$$\log(\text{duration}) = \mu + X_{\text{site}} + X_{\text{event}} + X_{\text{resid}} \quad . \tag{B-1}$$

The residual variance corresponds to variation between units during a single event. The estimated components of variance are given in Table B-6, in the column labeled Estimated Var. Comp. These are the estimated variances of the *X* terms in Equation (B-1). In each category, such as plant-centered events, the residual variation contributes very little to the total variance. Therefore, for events that caused loss of offsite power at two units, Table B-6 strongly suggests that the recovery times at the two units should be averaged, and only a single time should be used in the analysis.

Therefore, the model was simplified by averaging times that occurred for a single site event:

$$\log(\text{duration}) = \mu + X_{\text{site}} + X_{\text{event}} \quad . \tag{B-2}$$

The resulting values of the two components of variance are shown in Table B-7.

Table B-6. Estimated components of variance of $\log_{10}$(recovery time), for times ≥ 2 minutes.

Data set	Source of variation	Estimated Var. Comp.
Plant-centered, (107 reported recovery times by plant)		
	site	0.
	event	0.38
	resid.	0.003
Grid-related (5 reported recovery times by plant)		
	site	0.006
	event	0.030
	resid.	0.005
Severe-Weather (13 reported recovery times by plant)		
	site	0.16
	event	0.35
	resid.	0.014

Table B-7. Estimated components of variance of $\log_{10}$(recovery time), when times at multiple units are averaged for each event. Only times ≥ 2 minutes are considered here.

Data set	Source of variation	Estimated Var. Comp.
Plant-centered, (102 reported recovery times by site)		
	site	0.07
	event	0.32
Grid-related (4 reported recovery times by site)		
	site	0.006
	event	0.035
Severe-Weather (9 reported recovery times by site)		
	site	0.16
	event	0.36

In each case, the variance between sites is smaller than the variance of the individual events within a site. Therefore, we performed parametric and nonparametric analyses of variance, to see if the between-site differences were statistically significant. The conclusions were as follows.

For plant-centered recovery times, the analysis of variance gave a p-value of 0.09 (exact if the log-durations are normally distributed), and the Kruskal-Wallis test gave a p-value of 0.17 (based on an asymptotic approximation). Because the between-event variance was over 80% of the total variance, because the difference between sites did not appear to be statistically significant, and because a simple presentation is generally preferable, we ignored between-site differences and modeled all the variance of the recovery times as if it were between-event variance.

For grid events, we used only one component of variance. It is questionable whether the data should even be analyzed at all.

For severe-weather events, the same tests were performed as for the plant-centered data. The analysis of variance p-value and the Kruskal-Wallis p-value were similar, about 0.44, indicating no statistical evidence of between-site differences. (Recall that a small data set almost never shows strong statistical evidence of anything.) However, the components of variance did not appear so clear-cut. Therefore we tried modeling the two components of variance to obtain site-specific distributions for the recovery times. The site-specific 90% intervals overlapped greatly, and the ratio of the highest to the lowest site-specific median time was only 5.4. By contrast, the typical ratio of the site-specific 95th percentile to the 5th percentile was about 200. Finally, no engineering considerations did not give a reason why geography should affect the recovery times. In conclusion, modeling the between-site differences did not seem worth the trouble, so this report presents only a generic distribution of severe-weather recovery times.

In summary, a generic distribution of the non-momentary recovery times is presented for each of the three categories. For grid-related recovery times, a distribution is modeled in spite of reservations about the small size of the data set.

B-4.3 Forms of the Distributions

The Shapiro-Wilk test was applied to the plant-centered, grid-related, and severe-weather data, to determine whether ln(recovery time) was normally distributed. The p-values were 0.25, 0.23, and 0.59, respectively. This indicates no evidence of non-normality in any case. Therefore, other distributions, such as the Weibull or gamma, were not considered.

Figure B-17 plots the logarithm of the plant-centered non-momentary recovery times against the corresponding expected quantiles of a normal distribution. The smallest reported values, all 2 minutes, depart somewhat from the line, but the nearly straight line gives visual evidence that the fit is acceptable.

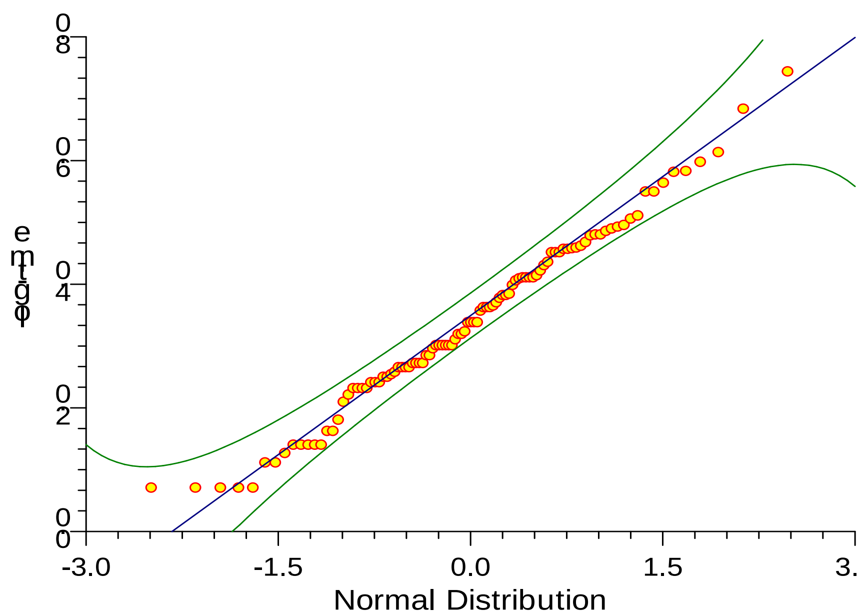

Figure B-17. Reported values of ln(recovery time) vs. normal quantiles, for plant-centered non-momentary trip and shutdown events. The band represents 95% confidence intervals (in the vertical direction) for the expected values of the ordered observations.

Similarly, Figure B-18 plots the logarithm of the severe-weather non-momentary recovery times against the corresponding expected quantiles of a normal distribution. There are too few data points to show any lack of fit to the assumed normal distribution.

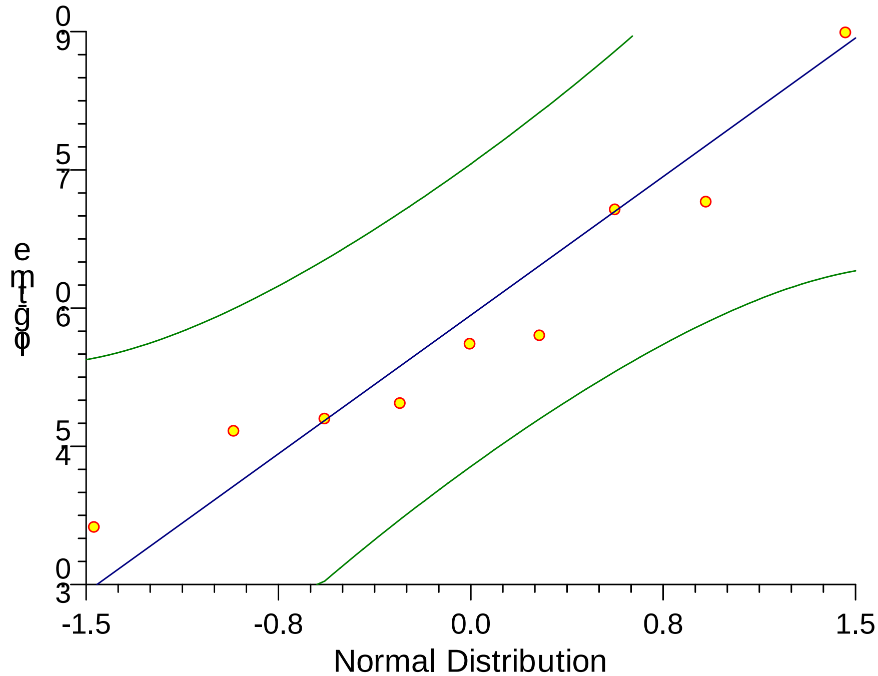

Figure B-18. Reported values of ln(recovery time) vs. normal quantiles, for severe-weather non momentary events. The band represents 95% confidence intervals (in the vertical direction) for the expected values of the ordered observations.

Figures B-19 and B-20 show the survival curves, for non-momentary events. The survival curve at time *t* is defined as the probability that the recovery time exceeds *t*; it is the same as the complementary cumulative distribution.

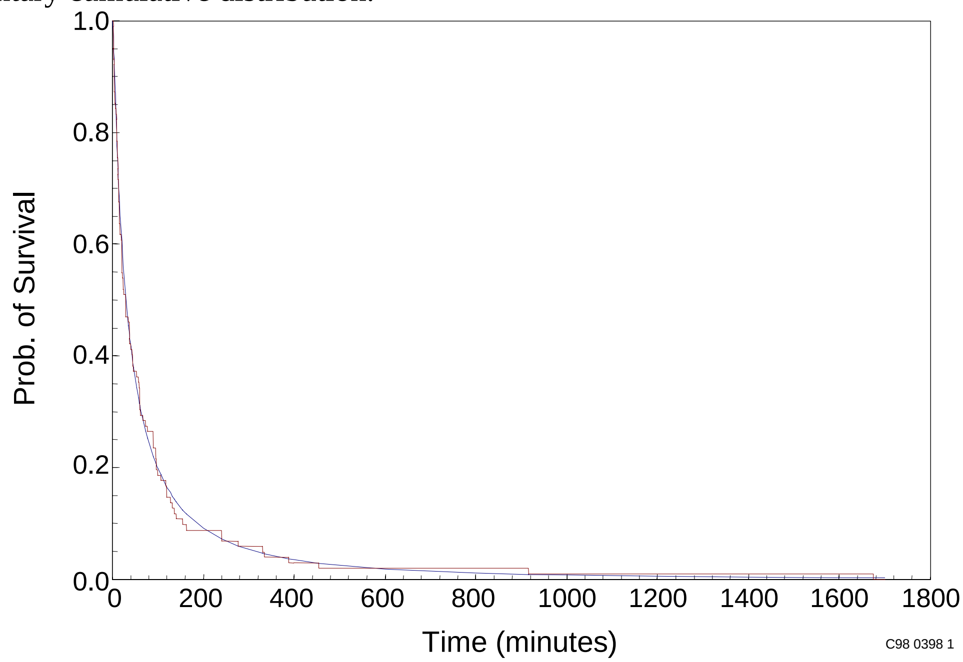

Figure B-19. Survival curve for plant-centered recovery times, empirical and fitted lognormal. This is based on non-momentary trip and shutdown events.

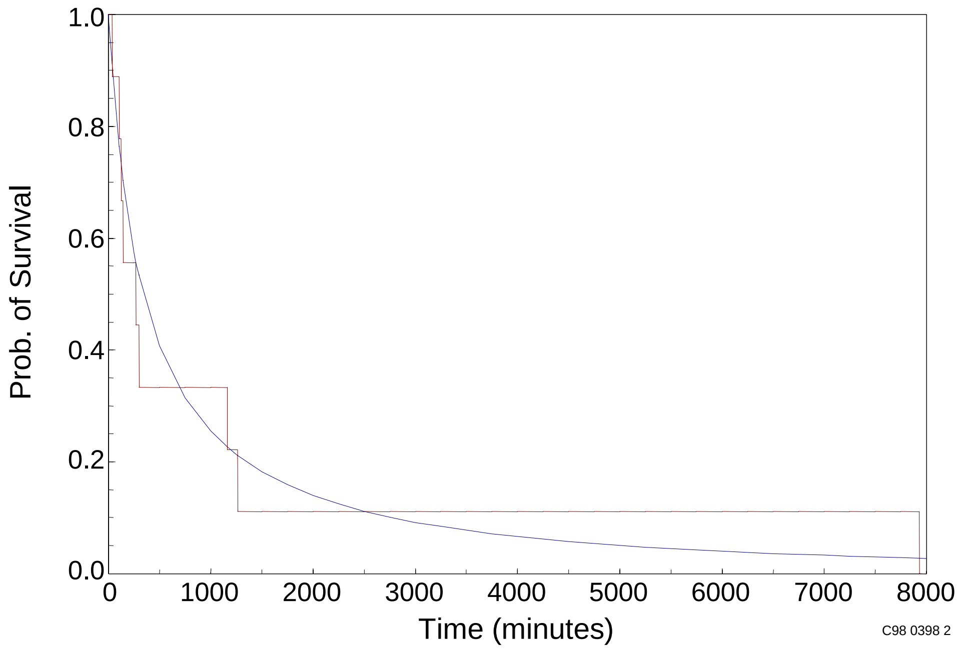

Figure B-20. Survival curve for severe-weather recovery times, empirical and fitted lognormal. This is based on non-momentary initiating and shutdown events.

Table B-8 summarizes the distributions that were finally estimated. The percentiles and means are expressed in minutes. The format is like that of Table B-2. For the lognormal distribution, the two parameters given are the *median*, and the error factor. The mean for each distribution is given in column 3, and the 5th and 95th percentiles in columns 2 and 4, all expressed in minutes.

Table B-8. Fitted distributions of recovery times of non-momentary LOSP events: Means, Percentiles, and Distributions. (See text for explanation.)

Category	5th %ile	mean	95th %ile	distribution and parameters[a]
Plant-centered events (102 site events with reported recovery times, single distribution modeled)				
Industry	2.80	82.9	313.7	lognormal[a](29.6 min., 10.6)
Grid-related events (only 4 site events with reported recovery times, two of which may be dependent. Uncertainty from lack of data is not accounted for. Interpret the results with care.)				
Industry	86.5	206.5	397.5	lognormal(185 min., 2.14)
Severe-weather events (9 site events with reported recovery times)				
Industry	23.15	1295.	5009.	lognormal(341 min., 14.7)

a. As explained in the text, the parameters shown for the lognormal distribution are the *median* and the error factor.

B-5 COMPARISONS WITH NUREG-1032

B-5.1 Frequencies of Plant-Centered Initiating Events

Frequencies of plant-centered initiating events were examined back to 1969. A set of plant calendar years from 1969 through 1979 is given by Modarres et al. (1996). The plant calendar years were also calculated from the INEEL unit information database, although some old plants are not contained in this database. For each year, the larger of the numbers from the two sources was used. Table B-9 lists the data used.

Table B-9. Plant-centered LOSP initiating events and reactor calendar years, by year.

Year	Events	Cal. Years	Year	Events	Cal. Years
1969	1	9.1	1984	6	81.9
1970	0	12.6	1985	5	90.1
1971	3	17.7	1986	3	96.8
1972	3	22.5	1987	4	102.7
1973	3	30.4	1988	4	107.7
1974	3	42.3	1989	4	109.0
1975	1	50.8	1990	0	110.5
1976	3	55.3	1991	6	111.0
1977	7	61.2	1992	6	110.4
1978	3	64.6	1993	4	108.7
1979	1	66.0	1994	0	109.0
1980	4	66.8	1995	0	109.0
1981	1	70.2	1996	1	110.1
1982	2	73.0			
1983	0	77.5	Total	78	2076.9

The trend in frequencies is shown in Figure B-21. The trend is statistically very significant (p-value = 0.0001). The fit is acceptable (p-value for testing adequacy of fit = 0.08).

The normalization is by reactor calendar years. It would have been better to normalize by reactor critical years, but those values were not readily available before 1981. The fraction of time when reactors are critical has increased since the late 1980s. Thus, the decreasing trend would appear slightly more pronounced if critical time had been used instead of calendar time.

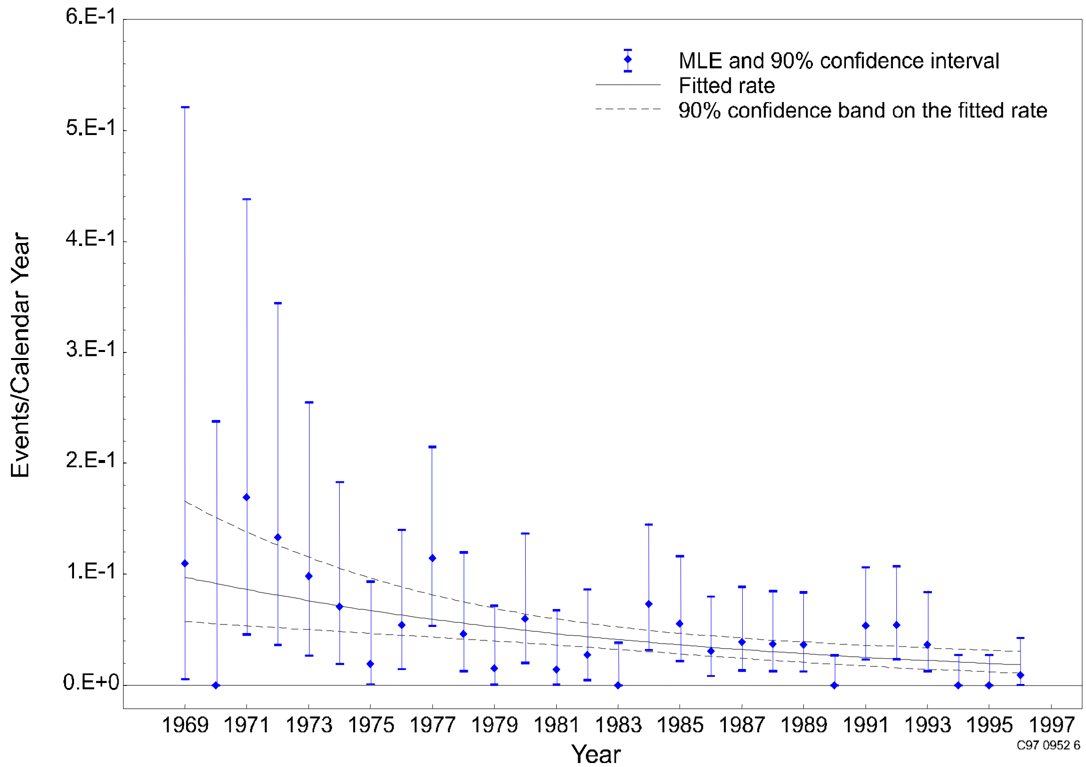

Figure B-21. Frequencies of plant-centered LOSP initiating events during power operation (events per unit calendar year). The trend is statistically very significant (p-value = 0.0001).

B-5.2 Data Used for Analysis of Recovery Times.

The recovery times from NUREG-1032 and from Table C-1 of this report, for events occurring in 1980-1985 were compared. Small discrepancies in times can arise from rounding off a conversion from minutes to hours in NUREG-1032 and then converting back to minutes for this table. Most of the differences between the two studies concern events that are included in the present report but not in NUREG-1032, or shutdown events that were presumably regarded as initiating events in NUREG-1032. Remaining differences in recovery times are matters of judgment concerning when power could have been restored, as determined by engineers with operational experience.

B-5.3 Frequencies of Durations of Initiating Events

The complementary cumulative frequency curves were plotted. A portion of the plot is shown in section 3 as Figure 3.9. That plot is truncated to have size and shape agreeing with the corresponding plot from NUREG-1032. The full plot is displayed here in Figure B-22.

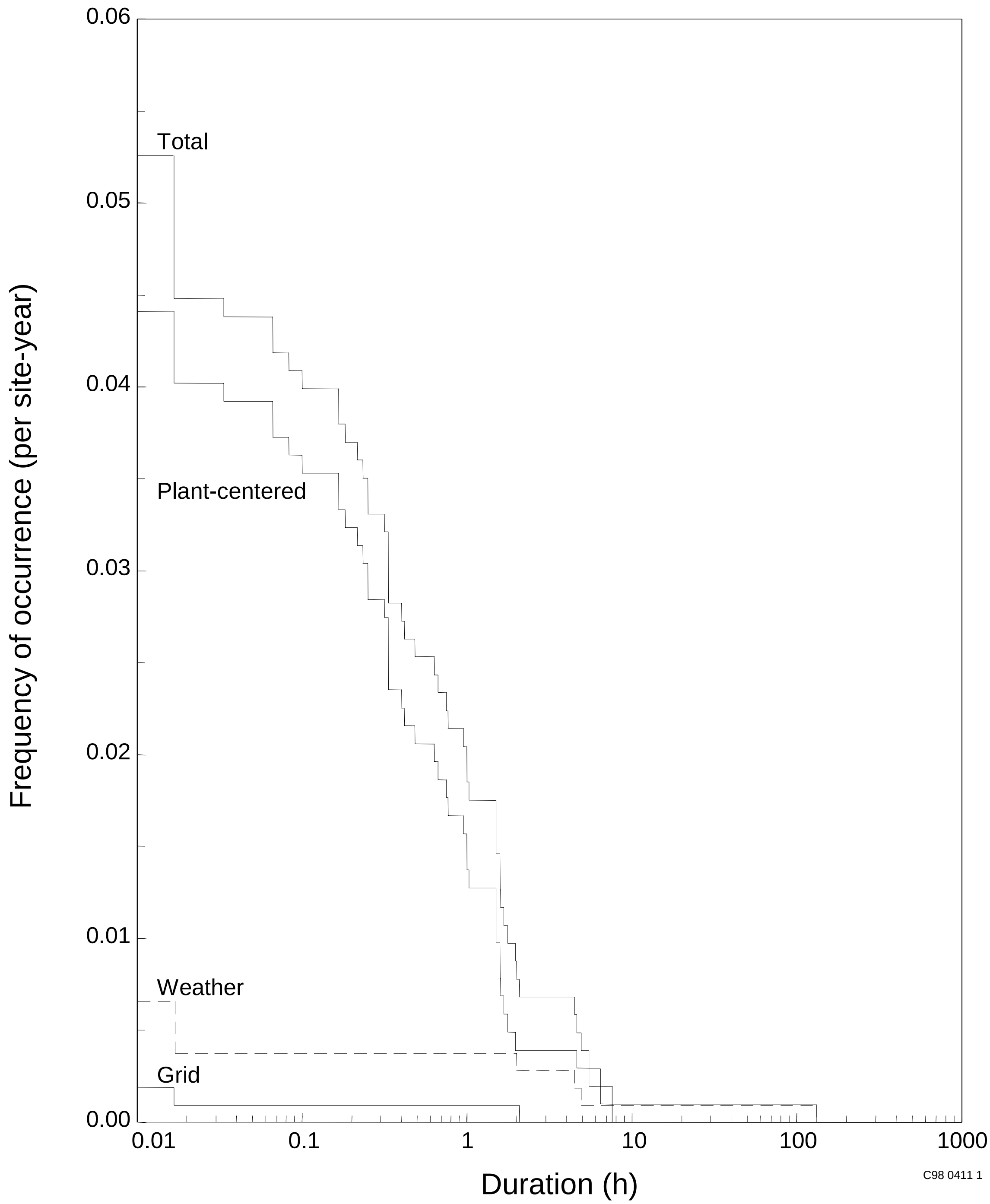

Figure B-22. Complementary cumulative frequency curves of site events, using 1980-1996 initiating event data.

B-5.4 Effect of Design Group on Recovery Times

NUREG-1032 defined three groups of plants, based on various design factors concerning offsite power sources and the existence of automatic transfer mechanisms. The categorization used for this report is given in Table C-6 of Appendix C.

Figures B-23 and B-24 show the logarithms of the recovery times for plant-centered non-momentary events, for each design group. Any differences seen are not statistically significant, by the Kruskal-Wallis test.

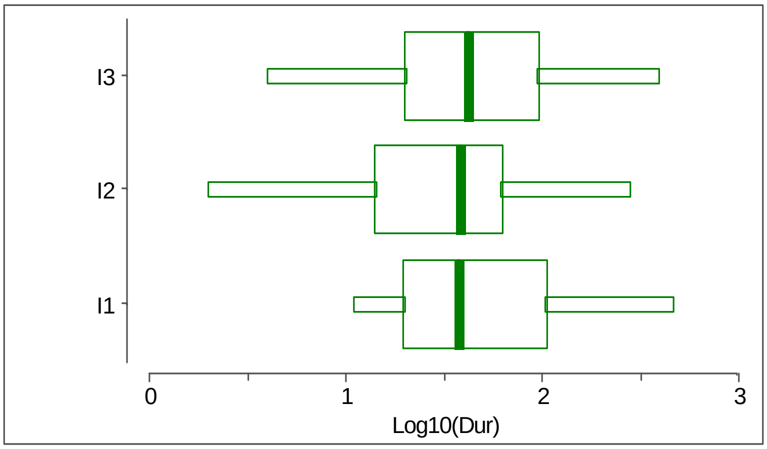

Figure B-23. $\log_{10}$(recovery time), for plant-centered trip events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.39).

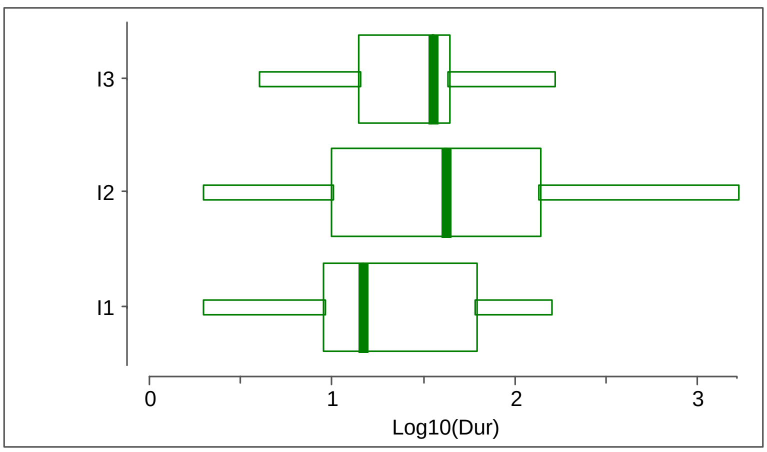

Figure B-24. $\log_{10}$(recovery time), for plant-centered shutdown events with recovery time ≥ 2 minutes, plotted by design group. The differences are not statistically significant (p-value = 0.37). The difference between groups I1 and I3 is also not statistically significant (p-value = 0.35).

Big Rock Point and La Crosse were especially difficult to fit into the classification scheme. When those two plants were dropped from consideration, the above conclusions concerning statistical significance changed very little, and not in any systematic way. Therefore, the results without Big Rock Point and La Crosse are not shown here.

One might conjecture that the design groups could make a difference in the fraction of LOSP events that are momentary. Table B-10 shows that this is not the case. The difference between design groups is not close to statistically significant, and no ordering of the design groups is apparent. Indeed, group I1 has the smallest fraction of momentary events instead of the expected largest, although any pattern seen could result from randomness alone. Pilgrim was excluded from this analysis, because it had so many momentary events that it would dominate the analysis.

Table B-10. Estimated probability that a random LOSP event is momentary.

Design Group	Momentary Events	All Events	Observed Fraction of Momentary Events	90%Conf. Int. on Prob(event is momentary)
Trip Events (p-value for difference between design groups = 0.46)				
I1	0	9	0.0	(0.00, 0.28)
I2	5	33	0.15	(0.06, 0.29)
I3	2	11	0.12	(0.02, 0.33)
Shutdown Events (p-value for difference between design groups = 0.40)				
I1	1	20	0.05	(0.003, 0.22)
I4	4	42	0.10	(0.03, 0.21)
I3	4	23	0.17	(0.06, 0.36)

B-6 REFERENCE

Modarres, M., H. Martz, and M. Kaminsky, 1996, “The Accident Sequence Precursor Analysis: Review of the Methods and New Insights,” *Nuclear Science and Engineering*, Vol. 123, pp. 238-258, (Table III).

APPENDIX C

SUMMARY OF DATA

This appendix provides details about the data included in the analyses. This includes information about how the source data were collected, the guidance for evaluation of the source data to identify and code the LOSP events, and the data that were obtained for the operating and shutdown times. All the event data that are in the tables of this appendix are contained in the LOSP database.

C-1 DATA COLLECTION AND CODING GUIDANCE

Identification of LOSP events was a multi-step process. The first step was to request from Oak Ridge National Laboratory the LER abstracts of all events in the SCSS database that involved some form of loss of electrical power, for the time period of this study. This request yielded approximately 4500 events for which the LER abstracts were reviewed by engineers with operational experience. There was no attempt to use SCSS to perform any screening or characterizations of the events, but only to identify those events that might involve some form of AC power failure at the plant. From the abstract review of these 4500 events, approximately 1400 events were identified involved a partial or complete loss of power to the plant. A more detailed review of these 1400 LER texts resulted in identification of the 176 events that met the criteria for inclusion in the analyses for this study, a simultaneous loss of electrical power to all unit safety buses, requiring the emergency power generators to start and supply power to the safety buses. All Class 1E EDGs, the Keowee hydro units at Oconee, and the gas turbine generator at Millstone 1 are considered emergency generators for this study.

Upon identification of an event as a LOSP event, all information needed for the analysis was coded and entered into a database. The coding guidance was developed by the engineers performing the event reviews, together with the statistical analysts, to ensure that all relevant information was included. The event information was loaded into a Microsoft ACCESS database. The database contains only the events that are within the scope of this study, as discussed in section 2 of the main report. (Partial loss of power events were not included in the database.) The database provides only the commercially available search and organizational capabilities of the ACCESS format. Specifically, the capabilities are the ability to store, sort, filter, and develop queries for the data present in a given field. No additional software development was provided. Analysis and trending of the data contained in the database was performed with other software tools. The following are the field identifiers and explanations of the coding details contained within this database:

- LER Number - The number of the report from which the event data was derived. For those events identified without an LER, the docket number, year, then three zeros is entered. For events affecting more than one unit but originating from a single LER, the LER number is listed separately for each unit with the same date, but the data is entered appropriately for each unit.

- Abstract - The LER abstract extracted from the SCSS without modification, if available. In some cases the LER abstract does not provide all the information needed for the study. Additional event information is contained in the “Notes” field but the full LER is still necessary for proper review of some events.

- Revision - This indicates the revision number of the LER used for the data review. Not all LERs listed have a revision listed because this field was added late during the data review.

- Source -
  EX = The event originated from the review of events considered external to the plant.
  IN = The event originated from the review of events considered internal to the plant.

- Site - The plant name without unit identifiers.

- Event date - Self evident.

- 1032 Category - The category taken from NUREG 1032 to which the event was classified.
  P - Plant-Centered
  G - Grid-Related
  W - Severe Weather

- 1032 Design Group - The electrical design group derived from NUREG-1032 Table A.2 and A.4, relating to the design features of the electrical system.

- Unit 1/2/3 Recovery Time - The time in minutes, from event initiation until the first offsite electrical power is available to restore a safety bus. This excludes power from the emergency power generators. This restoration time is NOT when the emergency generator is unloaded but rather the elapsed time until the bus could have been powered from an offsite source had the emergency generator failed. Many plants continue to use the emergency generators for safety bus power long after absolutely necessary, for a variety of reasons. In some cases the offsite power source was never lost but plant-centered events caused electrical isolation from the offsite sources. For these events, when equipment complications did not exist, a restoration time of one minute was established. This time is consistent with times stated in some LERs and licensed operator experience, and represents an estimation of the time necessary for a proficient operator to recognize that offsite power was available and restore at least one offsite power source to an emergency bus.

- Recovery Time - The same times listed in Unit 1/2/3 Recovery Time, combined into one field for ease of data reduction.

- Notes - A summary of relevant event information expressed by the reviewer. Those events that had an initial plant electrical system line up that increased the vulnerability to a loss of offsite power or may have increased the recovery time, include the phrase “(abnormal LU)” in this field. Operating events not used for reactor trip initiating event frequency analysis because the reactor trip preceded the electrical transient, but otherwise considered in data analysis, include the following in this field: “This event is not used for frequency estimation but is used for recovery times data”.

- References - Any reference used for event information other than LERs.

- Unit 1/2/3 EFF Status -

  TRIP = The electrical event caused a unit trip from power.

  TRIP* = The event occurred during unit hot shutdown. The event characteristics and plant configuration apply to power operation conditions. This includes cases in which the trip preceded the loss of offsite power.

  SHUTDOWN = The event occurred during unit cold shutdown .

  SHUTDOWN* = The event occurred during unit hot shutdown or during unit startup. The event characteristics and plant configuration apply to shutdown conditions.

  POWER OP = The event occurred during unit power operation and the unit remained at power.

- Unit Status - The same times listed in Unit 1/2/3 EFF Status, combined into one field for ease of data reduction.

- Cause -

  G = Interconnected grid transmission line events, outside direct plant control .

  EQUIP = Hardware related failures

  HE = Human error during any operating mode.

  HES = Human error during any shutdown mode.

  EEE = Extreme External Events: Hurricane, Winds > 125 mph, Tornado, Earthquake > R7, Flooding > 500 year flood for the site, Sabotage.

  SEE = Severe External Events: Lightening, High Winds, Snow and Ice, Salt Spray, Dust Contamination, Tree Interference, Fires and Smoke Contamination, Earthquake < R7, Flooding < 500 year flood for the site.

- Docket - Three digit docket number of the affected unit. This number does not always match the LER docket number.

Of the 176 events in the data base, three events occurred before the full power license date (35486011, 41682045, 44388004) and are not used in the data analysis. Of the remaining 173 events, 16 are excluded from the frequency analysis. The 11 “POWER OP” events occurred during power operation and challenged the emergency generators to power the safety buses, but they did not cause a reactor trip, thus were not considered initiating events. In five other events, a reactor trip from a non-electrical cause preceded the electrical event and actually triggered the transient resulting in the loss of offsite power. These 16 events are indicated by 0 in the "Initiator" column of Tables C-1 through C-3. They are used to characterize the recovery times for trip events, but not to estimate the frequency of initiating events.

C-2 EVENT TABLES

Tables C-1 through C-3 summarize the events contained in the LOSP database used for the analysis. Note that sometimes an LER number corresponds to more than one event, or to an event at more than one plant unit. The field explanations are as follows: The column field labeled "1032 Category" has value P, G, or W, for plant-centered, grid-related, or severe weather. In the column "Status," the entries P, S, S*, T, and T* are abbreviations for POWER OP, SHUTDOWN, SHUTDOWN*, TRIP, and TRIP*. The "Cause" field is self-explanatory, although the text in the field is too brief to provide a complete description of the event's cause. The column labeled "Initiator" has value 1 if the event is an initiating event, and 0 otherwise. This applies to status P, T, and T* only; it is irrelevant for shutdown events. The recovery time is given in minutes. For the analysis of recovery times, estimated times were treated as if they were actual times, and unknown times were ignored. The event date is written as month/day/year.

Table C-1. Plant-centered LOSP events.

LER Number	Plant Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
22082004	Nine Mile Pt. 1	P	P	Equip - breaker	0	1.0 C	02/07/82
22090023	Nine Mile Pt. 1	P	P	Equip - transformer	0	355	11/12/90
22093007	Nine Mile Pt. 1	P	P	SEE - lightning	0	1.0 C	08/31/93
24481007	Ginna	P	P	Equip - breaker	0	unknown	04/18/81
24488006	Ginna	P	P	Equip - transformer	0	65	07/16/88
25980019	Browns Ferry 3	P	P	SEE - wind	0	6	03/01/80
26685004	Point Beach 1	P	P	Equip - relay	0	45 C	07/25/85
28680008	Indian Point 3	P	P	SEE - Lightning	0	147	06/03/80
31194007	Salem 2	P	P	HE - testing	0	385	04/11/94
45796001	Braidwood 2	P	P	SEE - wind	0	113	01/18/96
52989001	Palo Verde 2	P	P	SEE - rain&cont	0	1138 C	01/03/89
2984008	Yankee-Rowe	P	S	HES - maintenance	-	5	05/03/84
15592000	Big Rock Point	P	S	Equip - other	-	77	01/29/92
20680015	San Onofre 1	P	S	HES - testing	-	4	04/22/80
20684038	San Onofre 1	P	S	HES - switching	-	0.25	11/22/80
21384009	Haddam Neck	P	S*	HES - switching	-	10	08/01/84
21384014	Haddam Neck	P	S	Equip - relay	-	22	08/24/84
21393009	Haddam Neck	P	S	Equip - circuits	-	12	06/22/93
21393010	Haddam Neck	P	S	Equip - circuits	-	3.0 est	06/26/93
21983000	Oyster Creek	P	S	Equip - other	-	240 C	11/14/83
21984021	Oyster Creek	P	S	HES - maintenance	-	unknown	09/25/84
24585027	Millstone 1	P	S	HES - testing	-	3.5	11/21/85
24589012	Millstone 1	P	S	HES - other, design	-	1.0 C	04/29/89
24783035	Indian Point 2	P	S*	Equip - relay	-	11.0	10/04/83
24791006	Indian Point 2	P	S	Equip - other	-	29	03/20/91
24791010	Indian Point 2	P	S	Equip - breaker	-	60	06/22/91
25085012	Turkey Point 3	P	S	HE - maintenance	-	335	04/29/85
25091003	Turkey Point 3	P	S	Equip - breaker	-	11	07/24/91
25191001	Turkey Point 4	P	S	Equip - relay	-	67	03/13/91
25584001	Palisades	P	S	HES - maintenance	-	97	01/08/84
25592032	Palisades	P	S	HES - testing	-	unknown	04/06/92
26381009	Monticello	P	S	HES - maintenance	-	15	04/27/81
26384021	Monticello	P	S	HES - testing	-	2	06/04/84
26585011	Quad Cities 2	P	S	HE - maintenance	-	43	05/07/85

Table C-1. (continued)

LER Number	Plant Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
26591005	Quad Cities 1	P	S	Equip - transformer	-	unknown	04/02/91
26592011	Quad Cities 2	P	S	Equip - transformer	-	35	04/02/92
26692003	Point Beach 1	P	S	HES - maintenance	-	10	04/28/92
26694010	Point Beach 2	P	S	HES - switching	-	1.0 C	09/27/94
27187008	Vermont Yankee	P	S	Equip - other	-	2.0 C	08/17/87
27284013	Salem 1	P	S	HE - switching	-	0.50	06/02/84
27284013	Salem 2	P	S	HE - switching	-	1.0 C	06/02/84
27284014	Salem 1	P	S	Equip - breaker	-	120	06/05/84
27591004	Diablo Canyon 1	P	S	HES - maintenance	-	240	03/07/91
27595014	Diablo Canyon 1	P	S	HES - maintenance	-	917	10/21/95
27788020	Peach Bottom 2	P	S	Equip - transformer	-	24	07/29/88
27788020	Peach Bottom 3	P	S	Equip - transformer	-	24	07/29/88
28587008	Fort Calhoun	P	S	HES - maintenance	-	37	03/21/87
28587009	Fort Calhoun	P	S	HES - maintenance	-	4	04/04/87
28590006	Fort Calhoun	P	S	HES - maintenance	-	14	02/26/90
28684015	Indian Point 3	P	S	SEE - wind,debris	-	14	11/16/84
28695004	Indian Point 3	P	S	HE - maintenance	-	132	02/27/95
28696002	Indian Point 3	P	S	Equip - transformer	-	127	01/20/96
28785002	Oconee 3	P	S	Equip - transformer	-	73	08/28/85
28787002	Oconee 3	P	S	HES - maintenance	-	155	03/05/87
29383045	Pilgrim	P	S	SEE - lightning	-	1.0 C	08/02/83
29384017	Pilgrim	P	S	HES - testing	-	15	12/19/84
29386029	Pilgrim	P	S	HE - maintenance	-	1.0	12/23/86
29389010	Pilgrim	P	S	Equip - other	-	1.0 C	02/21/89
29393010	Pilgrim	P	S	HES - testing	-	37	05/19/93
30184005	Point Beach 2	P	S	HES - testing	-	3.0	10/22/84
30287025	Crystal River 3	P	S	HES - maintenance	-	59	10/16/87
30289023	Crystal River 3	P	S*	HES - testing	-	60	06/16/89
30289025	Crystal River 3	P	S*	SEE - lightning	-	2	06/29/89
30291010	Crystal River 3	P	S	HES – other (construct)	-	4	10/20/91
30293004	Crystal River 3	P	S	HES - maintenance	-	136	04/08/93
30480001	Zion 2	P	S	SEE - wind	-	unknown	01/13/80
30680020	Prairie Island 1	P	S	SEE - lightning	-	62	07/15/80
31194014	Salem 2	P	S	Equip - relay	-	1675	11/18/94
32181026	Hatch 1	P	S	Equip - relay	-	unknown	04/05/81
32494008	Brunswick 2	P	S	HES - testing	-	2	05/21/94
32583023	Brunswick 1	P	S	HES - testing	-	17	04/26/83
33190007	Duane Arnold	P	S	HES - testing	-	37	07/09/90
33493013	Beaver Valley 2	P	S	HES - maintenance	-	15	10/12/93
33686017	Millstone 2	P	S	HES - maintenance	-	unknown	11/05/86
34881001	Farley 1	P	S	HES - maintenance	-	unknown	01/16/81
36483047	Farley 2	P	S	Equip - breaker	-	163	10/08/83
36987021	McGuire 1	P	S	HES - testing	-	29	09/16/87
36988014	McGuire 2	P	S	HES - switching	-	8	06/24/88
38285054	Waterford 3	P	S	SEE - lightning	-	1.0 C	12/12/85
39789016	Wash. Nuclear 2	P	S	HES - maintenance	-	29	05/14/89
40981001	La Crosse	P	S*	Equip - breaker	-	120	01/16/81
40981002	La Crosse	P	S*	HES - switching	-	14	02/01/81
40981014	La Crosse	P	S*	Equip - breaker	-	10	12/23/81
40986023	La Crosse	P	S	SEE - lightning	-	12	07/19/86
41088062	Nine Mile Pt. 2	P	S	Equip - transformer	-	9	12/26/88
41092006	Nine Mile Pt. 2	P	S	HES - maintenance	-	20	03/23/92
42490006	Vogtle 1	P	S	HE - other	-	140	03/20/90
45496007	Byron 1	P	S*	Equip - transformer	-	1.0 C	05/23/96
45587019	Byron 2	P	S*	HE - switching	-	1.0 C	10/02/87
45687048	Braidwood 1	P	S*	Equip - transformer	-	53	09/11/87
48287048	Wolf Creek	P	S	HES - maintenance	-	17.0 est	10/14/87
2991002	Yankee-Rowe	P	T	SEE - lightning	1	24	06/15/91
20685017	San Onofre 1	P	T	Equip - transformer	1	4	11/21/85
21989015	Oyster Creek	P	T	HE - maintenance	1	1.0	05/18/89
21992005	Oyster Creek	P	T	SEE - fire	1	6	05/03/92
23785034	Dresden 2	P	T	Equip - transformer	1	5	08/16/85
23790002	Dresden 2	P	T*	Equip - transformer	0	45 C	01/16/90
24780006	Indian Point 2	P	T	SEE - lightning	1	106	06/03/80
24785016	Indian Point 2	P	T*	HES - other	0	20	12/12/85
24989001	Dresden 3	P	T	Equip - breaker	1	45 C	03/25/89
25084006	Turkey Point 3	P	T	Equip - relay	1	90	02/12/84
25084007	Turkey Point 3	P	T	HE - switching	1	15 C	02/16/84
25482012	Quad Cities 2	P	T	Equip - relay	1	29	06/22/82
25587024	Palisades	P	T	HE - maintenance	1	388	07/14/87

26186005	Robinson 2	P	T	Equip - relay	1	100	01/28/86

Table C-1. (continued)

LER Number	Plant Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
26192017	Robinson 2	P	T	Equip - transformer	1	454	08/22/92
27092004	Oconee 2	P	T	HE - maintenance	1	57.0	10/19/92
27191009	Vermont Yankee	P	T	HE - maintenance	1	277	04/23/91
27283033	Salem 1	P	T*	Equip - transformer	0	1.0 C	08/11/83
29393022	Pilgrim	P	T	SEE - lightning	1	10	09/10/93
30189002	Point Beach 2	P	T	HE - maintenance	1	90 C	03/29/89
30281033	Crystal River 3	P	T	SEE - lightning	1	unknown	06/16/81
30284003	Crystal River 3	P	T	Equip - transformer	1	2	02/28/84
30292001	Crystal River 3	P	T	HE - maintenance	1	20 C	03/27/92
30491002	Zion 2	P	T	Equip - transformer	1	60	03/21/91
30680020	Prairie Island 2	P	T	SEE - lightning	1	62	07/15/80
30988006	Maine Yankee	P	T	Equip - transformer	1	14	08/13/88
31186007	Salem 2	P	T*	Equip - other,design	0	1.0 C	08/26/86
31380022	Arkansas 1	P	T	Equip - breaker	1	unknown	06/24/80
31380022	Arkansas 2	P	T	Equip - breaker	1	unknown	06/24/80
31591004	Cook 1	P	T	Equip - other	1	1.0 C	05/12/91
31787012	Calvert Cliffs 1	P	T	Equip - circuits	1	118	07/23/87
31787012	Calvert Cliffs 2	P	T	Equip - circuits	1	118	07/23/87
32388008	Diablo Canyon 2	P	T	Equip - transformer	1	38	07/17/88
32489009	Brunswick 2	P	T	HE - maintenance	1	90 C	06/17/89
32586024	Brunswick 1	P	T	Equip – circuits	1	1.0 C	09/13/86
32792027	Sequoyah 1	P	T	Equip - breaker	1	95	12/31/92
32792027	Sequoyah 2	P	T	Equip - breaker	1	95	12/31/92
33493013	Beaver Valley 1	P	T	HE - maintenance	1	10	10/12/93
33582041	St. Lucie 1	P	T	Equip - breaker	1	1.0 C	09/07/82
33688011	Millstone 2	P	T	HE - maintenance	1	19	10/25/88
36984024	McGuire 1	P	T	Equip - circuits	1	20	08/21/84
36991001	McGuire 1	P	T	HE - testing	1	40	02/11/91
37093008	McGuire 2	P	T	Equip - transformer	1	96	12/27/93
37393015	Lasalle 1	P	T	Equip - transformer	1	15 C	09/14/93
38884013	Susquehanna 2	P	T	HE - testing	1	11.0	07/26/84
40984011	La Crosse	P	T*	Other - mayflies	1	20	07/16/84
40985017	La Crosse	P	T	HE - maintenance	1	60	10/22/85
41287036	Beaver Valley 2	P	T	Equip - breaker	1	4.0 C	11/17/87
41496001	Catawba 2	P	T	Equip - transformer	1	330	02/06/96
44391008	Seabrook	P	T	Equip - relay	1	20	06/27/91
45688022	Braidwood 1	P	T	Equip - breaker	1	95	10/16/88
45886002	River Bend	P	T*	Equip - circuits	1	46	01/01/86
52885058	Palo Verde 1	P	T	Equip - circuits	1	25	10/03/85
52885076	Palo Verde 1	P	T*	Equip - circuits	1	13	10/07/85

Table C-2. Grid-related LOSP events.

LER number	Plant Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
25185011	Turkey Point 3	G	S	G-Other - fire	-	156	05/17/85
31281034	Rancho Seco	G	S*	G-Other - load	-	360	06/19/81
31281039	Rancho Seco	G	S*	G-Other - load	-	180	08/07/81
25185011	Turkey Point 4	G	T	G-Other - fire	1	125	05/17/85
33184028	Duane Arnold	G	T*	G-Equip - other	1	1.0 C	07/14/84
39589012	Summer	G	T*	G-Equip - other	0	130	07/11/89

Table C-3. Weather-related LOSP events.

LER number	Plant Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
26783018	Fort St. Vrain	W	S	SEE - Snow and wind	-	105	05/17/83
29382051	Pilgrim	W	S	SEE - wind, salt	-	1.0 C	10/12/82
29386027	Pilgrim	W	S	SEE - ice	-	1.0 C	11/19/86
29387005	Pilgrim	W	S	SEE - wind	-	1.0 C	03/31/87
29387014	Pilgrim	W	S	SEE - wind, salt	-	1263	11/12/87
30293000	Crystal River 3	W	S	SEE - wind, salt	-	unknown	03/13/93
30293000	Crystal River 3	W	S	SEE - rain, salt	-	72	03/17/93
30293002	Crystal River 3	W	S	SEE - storm flooding	-	37	03/29/93
32593008	Brunswick 2	W	S	SEE - wind, salt	-	814	03/16/93

LER Number	Plant Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
32593008	Brunswick 1	W	S	SEE - wind, salt	-	1508	03/16/93

Table C-3. (continued)

LER Number	Plant Name	1032 Category	Status	Cause	Initiator	Recovery Time	Event Date
33388011	Fitzpatrick	W	S	SEE - wind	-	1.5 C	10/31/88
24585018	Millstone 1	W	T*	EEE - hurricane	1	211 C	09/27/85
24585018	Millstone 2	W	T*	EEE - hurricane	1	330 C	09/27/85
25092000	Turkey Point 3	W	T*	EEE - hurricane	1	7950	08/24/92
25092000	Turkey Point 4	W	T*	EEE - hurricane	1	7908	08/24/92
28296012	Prairie Island 1	W	T	SEE - wind	1	296	06/29/96
28296012	Prairie Island 2	W	T	SEE - wind	1	296	06/29/96
29383007	Pilgrim	W	T	SEE - wind, salt	1	1.0 C	02/13/83
29391024	Pilgrim	W	T*	SEE - wind, salt	1	120	10/30/91
29393004	Pilgrim	W	T	SEE - snow	1	1.0 C	03/13/93
31380013	Arkansas 1	W	T	EEE - tornado	1	1.0 C	04/07/80
31380013	Arkansas 2	W	T	EEE - tornado	1	1.0 C	04/07/80

The critical hours, shutdown hours, and calendar hours used are summarized in Tables C-4 and C-5. Because no information was found for critical hours and shutdown hours in 1980, the critical hours and shutdown hours cover the period from 1981 through 1996. A year was defined as 365

Table C-4. Reactor-years for the study, by calendar year.

Year	Calendar Years	Critical Years	Shutdown Years
1980	66.833	.	.
1981	70.151	48.599	21.552
1982	72.973	48.754	24.219
1983	77.451	51.343	26.108
1984	81.904	52.991	28.913
1985	90.114	62.176	27.938
1986	96.807	63.814	32.993
1987	102.722	70.173	32.549
1988	107.688	76.428	31.260
1989	108.963	76.358	32.605
1990	110.510	80.624	29.886
1991	111.000	83.944	27.056
1992	110.370	83.836	26.534
1993	108.738	82.868	25.871
1994	109.000	85.801	23.199
1995	109.000	88.841	20.159
1996	110.123	87.299	22.824
Total	1644.345	1143.846[a]	433.667[a]

a. The total critical years plus shutdown years sum to 1577.513, which is the total calendar years excluding 1980. In 1980, 67% of the calendar time is estimated to have been critical time. This gives an estimated 1188.624 critical years and 455.722 shutdown years from 1980 – 1996.

days, or 8760 hours; that is, a critical year was 8760 critical hours for a reactor, a shutdown year was 8760 shutdown hours for a reactor, and a calendar year was 8760 calendar hours at a reactor. A consequence of this is that the period from 1980 through 1996 contains 17.014 calendar years, because of the leap years.

The events and exposure times are summarized for each plant in Table C-5. This table includes all the events used in the study, from 1980 through 1986. Therefore, the critical times and shutdown times are estimated for each plant, using the actual times for 1981 through 1996, and estimating the critical time for 1980 for each plant as 67% of the calendar time. To highlight the events that actually occurred, all zero counts are shown as hyphens.

Table C-5. Summary of LOSP events, by plant.

	Power Operation Experience				Shutdown Experience			
Unit	Plant-Centered[a]	Grid-Related[a]	Severe Weather[a]	Critical Years[b]	Plant-Centered[c]	Grid-Related[c]	Severe Weather[c]	Shutdown Years[b]
Arkansas 1	1, -	-, -	1, -	13.054	-	-	-	3.960
Arkansas 2	1, -	-, -	1, -	13.252	-	-	-	3.762
Beaver Valley 1	1, -	-, -	-, -	12.770	-	-	-	4.244
Beaver Valley 2	1, -	-, -	-, -	7.884	1	-	-	1.506
Big Rock Point	-, -	-, -	-, -	13.041	1	-	-	3.973
Braidwood 1	1, -	-, -	-, -	7.228	1	-	-	2.280
Braidwood 2	-, 1	-, -	-, -	7.290	-	-	-	1.333
Browns Ferry 1	-, -	-, -	-, -	3.493	-	-	-	13.521
Browns Ferry 2	-, -	-, -	-, -	8.415	-	-	-	8.599
Browns Ferry 3	-, 1	-, -	-, -	3.944	-	-	-	13.070
Brunswick 1	1, -	-, -	-, -	10.548	1	-	1	6.466
Brunswick 2	1, -	-, -	-, -	11.054	1	-	1	5.960
Byron 1	-, -	-, -	-, -	9.770	1	-	-	2.116
Byron 2	-, -	-, -	-, -	8.630	1	-	-	1.297
Callaway	-, -	-, -	-, -	10.704	-	-	-	1.509
Calvert Cliffs 1	1, -	-, -	-, -	11.877	-	-	-	5.136
Calvert Cliffs 2	1, -	-, -	-, -	12.224	-	-	-	4.790
Catawba 1	-, -	-, -	-, -	9.163	-	-	-	2.800
Catawba 2	1, -	-, -	-, -	8.408	-	-	-	2.232
Clinton 1	-, -	-, -	-, -	6.753	-	-	-	2.484
Comanche Peak 1	-, -	-, -	-, -	5.500	-	-	-	1.216
Comanche Peak 2	-, -	-, -	-, -	2.980	-	-	-	0.761
Cook 1	1, -	-, -	-, -	12.867	-	-	-	4.146
Cook 2	-, -	-, -	-, -	11.875	-	-	-	5.139
Cooper	-, -	-, -	-, -	12.077	-	-	-	4.937
Crystal River 3	3, -	-, -	-, -	11.790	5	-	3	5.224
Davis-Besse	-, -	-, -	-, -	11.605	-	-	-	5.409
Diablo Canyon 1	-, -	-, -	-, -	10.113	2	-	-	2.034
Diablo Canyon 2	1, -	-, -	-, -	9.601	-	-	-	1.757
Dresden 2	1, 1	-, -	-, -	11.392	-	-	-	5.622
Dresden 3	1, -	-, -	-, -	11.339	-	-	-	5.675
Duane Arnold	-, -	1, -	-, -	13.103	1	-	-	3.910
Farley 1	-, -	-, -	-, -	14.129	1	-	-	2.885
Farley 2	-, -	-, -	-, -	13.573	1	-	-	2.193
Fermi 2	-, -	-, -	-, -	7.161	-	-	-	4.309
Fitzpatrick	-, -	-, -	-, -	12.073	-	-	1	4.940
Fort Calhoun	-, -	-, -	-, -	13.393	3	-	-	3.620
Fort St. Vrain	-, -	-, -	-, -	3.753	-	-	1	5.914
Ginna	-, 2	-, -	-, -	13.828	-	-	-	3.185
Grand Gulf	-, -	-, -	-, -	10.075	-	-	-	2.269
Haddam Neck	-, -	-, -	-, -	12.290	4	-	-	4.648
Harris	-, -	-, -	-, -	8.337	-	-	-	1.640
Hatch 1	-, -	-, -	-, -	12.992	1	-	-	4.022
Hatch 2	-, -	-, -	-, -	13.289	-	-	-	3.724
Hope Creek	-, -	-, -	-, -	8.633	-	-	-	1.812
Indian Point 2	1, 1	-, -	-, -	12.525	3	-	-	4.489

Table C-5. (continued)

Unit	Power Operation Experience: Plant-Centered[a]	Grid-Related[a]	Severe Weather[a]	Critical Years[b]	Shutdown Experience: Plant-Centered[c]	Grid-Related[c]	Severe Weather[c]	Shutdown Years[b]
Indian Point 3	-, 1	-, -	-, -	9.059	3	-	-	7.954
Kewaunee	-, -	-, -	-, -	14.402	-	-	-	2.611
La Crosse	2, -	-, -	-, -	5.053	4	-	-	2.280
Lasalle 1	1, -	-, -	-, -	10.366	-	-	-	4.030
Lasalle 2	-, -	-, -	-, -	9.234	-	-	-	3.551
Limerick 1	-, -	-, -	-, -	9.543	-	-	-	1.864
Limerick 2	-, -	-, -	-, -	6.620	-	-	-	0.738
Maine Yankee	1, -	-, -	-, -	12.730	-	-	-	4.284
McGuire 1	2, -	-, -	-, -	11.433	1	-	-	4.062
McGuire 2	1, -	-, -	-, -	10.780	1	-	-	2.829
Millstone 1	-, -	-, -	1, -	12.512	2	-	-	4.502
Millstone 2	1, -	-, -	1, -	10.818	1	-	-	6.195
Millstone 3	-, -	-, -	-, -	7.748	-	-	-	3.177
Monticello	-, -	-, -	-, -	13.745	2	-	-	3.269
Nine Mile Pt. 1	-, 3	-, -	-, -	10.786	-	-	-	6.228
Nine Mile Pt. 2	-, -	-, -	-, -	6.855	2	-	-	2.653
North Anna 1	-, -	-, -	-, -	12.787	-	-	-	4.227
North Anna 2	-, -	-, -	-, -	13.540	-	-	-	2.834
Oconee 1	-, -	-, -	-, -	13.710	-	-	-	3.304
Oconee 2	1, -	-, -	-, -	13.892	-	-	-	3.122
Oconee 3	-, -	-, -	-, -	13.414	2	-	-	3.599
Oyster Creek	2, -	-, -	-, -	10.879	2	-	-	6.135
Palisades	1, -	-, -	-, -	10.260	2	-	-	6.753
Palo Verde 1	2, -	-, -	-, -	7.780	-	-	-	3.813
Palo Verde 2	-, 1	-, -	-, -	7.675	-	-	-	3.023
Palo Verde 3	-, -	-, -	-, -	7.050	-	-	-	2.058
Peach Bottom 2	-, -	-, -	-, -	10.704	1	-	-	6.309
Peach Bottom 3	-, -	-, -	-, -	10.663	1	-	-	6.350
Perry	-, -	-, -	-, -	6.969	-	-	-	3.172
Pilgrim	1, -	-, -	3, -	10.264	5	-	4	6.749
Point Beach 1	-, 1	-, -	-, -	14.299	1	-	-	2.715
Point Beach 2	1, -	-, -	-, -	14.283	2	-	-	2.731
Prairie Island 1	-, -	-, -	1, -	15.004	1	-	-	2.009
Prairie Island 2	1, -	-, -	1, -	14.948	-	-	-	2.065
Quad Cities 1	-, -	-, -	-, -	12.502	1	-	-	4.512
Quad Cities 2	1, -	-, -	-, -	12.200	2	-	-	4.814
Rancho Seco	-, -	-, -	-, -	3.932	-	2	-	5.508
River Bend	1, -	-, -	-, -	8.222	-	-	-	2.900
Robinson 2	2, -	-, -	-, -	11.682	-	-	-	5.332
Salem 1	-, 1	-, -	-, -	10.682	2	-	-	6.332
Salem 2	-, 2	-, -	-, -	9.306	2	-	-	6.323
San Onofre 1	1, -	-, -	-, -	6.061	2	-	-	6.864
San Onofre 2	-, -	-, -	-, -	11.480	-	-	-	2.847
San Onofre 3	-, -	-, -	-, -	10.676	-	-	-	2.627
Seabrook	1, -	-, -	-, -	5.648	-	-	-	1.156
Sequoyah 1	1, -	-, -	-, -	9.499	-	-	-	6.801
Sequoyah 2	1, -	-, -	-, -	9.783	-	-	-	5.523
South Texas 1	-, -	-, -	-, -	5.980	-	-	-	2.805
South Texas 2	-, -	-, -	-, -	5.453	-	-	-	2.316
St. Lucie 1	1, -	-, -	-, -	13.143	-	-	-	3.871
St. Lucie 2	-, -	-, -	-, -	11.508	-	-	-	2.064
Summer	-, -	-, 1	-, -	11.760	-	-	-	2.386
Surry 1	-, -	-, -	-, -	12.576	-	-	-	4.438
Surry 2	-, -	-, -	-, -	12.676	-	-	-	4.338
Susquehanna 1	-, -	-, -	-, -	11.289	-	-	-	2.857
Susquehanna 2	1, -	-, -	-, -	10.390	-	-	-	2.132
Three Mile Isl 1	-, -	-, -	-, -	10.557	-	-	-	6.457
Trojan	-, -	-, -	-, -	7.824	-	-	-	5.187
Turkey Point 3	2, -	-, -	1, -	11.251	2	1	-	5.763
Turkey Point 4	-, -	1, -	1, -	11.427	1	-	-	5.586
Vermont Yankee	1, -	-, -	-, -	14.060	1	-	-	2.954
Vogtle 1	-, -	-, -	-, -	8.566	1	-	-	1.238
Vogtle 2	-, -	-, -	-, -	6.957	-	-	-	0.806

Table C-5. (continued)

	Power Operation Experience				Shutdown Experience			
Unit	Plant-Centered[a]	Grid-Related[a]	Severe Weather[a]	Critical Years[b]	Plant-Centered[c]	Grid-Related[c]	Severe Weather[c]	Shutdown Years[b]
Wash. Nuclear 2	-, -	-, -	-, -	9.111	1	-	-	3.617
Waterford 3	-, -	-, -	-, -	9.818	1	-	-	1.986
Watts Bar 1	-, -	-, -	-, -	0.762	-	-	-	0.138
Wolf Creek	-, -	-, -	-, -	9.506	1	-	-	2.079
Yankee-Rowe	1, -	-, -	-, -	9.581	1	-	-	2.582
Zion 1	-, -	-, -	-, -	11.268	-	-	-	5.746
Zion 2	1, -	-, -	-, -	11.888	1	-	-	5.126
Total	50,15	2, 1	11, -	1188.624	80	3	11	455.722

a. For power operation experience, each pair of counts is the number of LOSP initiating events and the number of LOSP non-initiators. A hyphen indicates a count of zero.
b. Tabulated times assume that each reactor was critical for 67% of its calendar time in 1980.
c. For shutdown experience, each count is the number of LOSP events, regardless of whether or not those events would have caused a reactor trip at power. A hyphen indicates a count of zero.

Sites were categorized by electrical design group, I1, I2, I3, for an investigation of whether the design features of a plant affected the duration of plant-centered LOSP events. The categorized sites are listed in Table C-6. To the extent possible, the classification of NUREG-1032 was used, found in Tables A.2, A.3, and A.4 of that report. Sites that were not classified in NUREG-1032 are marked by an asterisk (*). Sites for which no LOSP events were identified for this study and that were not categorized by NUREG-1032 are not included in Table C-6.

Table C-6. Sites listed by design group. Site names preceded by * were categorized for this report. Those without the * were categorized in NUREG-1032 and the same categorization was used in this study.

I1	I2	I3
Haddam Neck	Arkansas	* Braidwood
Indian Point	Beaver Valley	* Byron
Millstone	* Big Rock Point	* Calvert Cliffs
Monticello	* Browns Ferry	* Catawba
Nine Mile Pt.	Brunswick	* Duane Arnold
Oconee	* Cook	Farley
* Robinson	* Crystal River	Fort Calhoun
Susquehanna	* Diablo Canyon	* La Crosse
* Yankee-Rowe	Dresden	Palisades
	* Fitzpatrick	Palo Verde
	* Fort St. Vrain	* Pilgrim
	Ginna	Quad Cities
	* Grand Gulf	San Onofre
	* Hatch	* Seabrook
	* Lasalle	* Sequoyah
	* Maine Yankee	* St. Lucie
	McGuire	* Waterford
	Oyster Creek	* Wolf Creek
	* Peach Bottom	* Zion
	Point Beach	
	Prairie Island	
	Rancho Seco	
	* River Bend	
	* Salem	
	* Summer	
	Turkey Point	
	* Vermont Yankee	
	* Vogtle	
	Wash. Nuclear	